6 Making Schools Safe From High Winds

6.1 General Design Considerations

Wind with sufficient speed to cause damage to weak schools can occur anywhere in the United States and its territories.[1] Even a well-designed, constructed, and maintained school may be damaged by a wind event much stronger than one the building was designed for. However, except for tornado damage, this scenario is a rare occurrence. Rather, most damage occurs because various building elements have limited wind resistance due to inadequate design, poor installation, or material deterioration. Although the magnitude and frequency of strong windstorms vary by locale, all schools should be designed, constructed, and maintained to minimize wind damage (other than that associated with tornadoes—see Section 6.5).

1 The U.S. territories include American Samoa, Guam, Northern Mariana Islands, Puerto Rico, and the U.S. Virgin Islands. ASCE 7 provides basic wind speed criteria for all but Northern Mariana Islands.

This chapter discusses structural, building envelope, and nonstructural building systems, and illustrates various types of wind-induced damage that affect them. Numerous examples of best practices pertaining to new and existing schools are presented as recommended design guidelines. Incorporating those practices applicable to specific projects will result in greater wind-resistance reliability and will, therefore, decrease expenditures for repair of wind-damaged facilities, provide enhanced protection for occupants, and avoid school disruption (see Figure 6-1).

The recommendations presented in this design guide are based on field observation research conducted on a large number of schools that were struck by hurricanes.[3] The recommendations are also based on numerous investigations of other types of critical and non-critical facilities exposed to hurricanes, tornadoes, and straight-line winds, and on literature review. Some of the schools were exposed to extremely high wind speeds, while others experienced moderate speeds.

Figure 6-1:
Large portions of the roof coverings blew off of this school. Estimated wind speed: Approximately 125 to 130 miles per hour (mph).[2] Hurricane Katrina (Louisiana, 2005)

2 Estimated speeds given in this chapter are for a 3-second gust at a 33-foot elevation for Exposure C (as defined in ASCE 7). In most instances, the buildings for which estimated speeds are given are located in Exposure B. Hence, in most cases, the actual wind speed was less than the wind speed given for Exposure C conditions. For example, a 130-mph Exposure C speed is equivalent to 110 mph in Exposure B.

3 The research on the schools was conducted by a team from Texas Tech University (Hurricane Hugo, Charleston, SC, 1989), a team under the auspices of the Wind Engineering Research Council—now known as the American Association for Wind Engineering (Hurricane Andrew, South Florida, 1992), and teams deployed by FEMA (Hurricane Marilyn, U.S. Virgin Islands, 1995; Typhoon Paka, Guam, 1997; Hurricane Charley, Port Charlotte, FL, 2004; Hurricane Frances, east coast of Florida, 2004; Hurricane Ivan, Pensacola, FL, 2004; Hurricane Katrina, Louisiana and Mississippi, 2005; and Hurricane Ike, Texas, 2008).

6.1.1 Nature of High Winds

A variety of windstorm types occur in different areas of the United States. The characteristics of the types of storms that can affect the site should be considered by the design team. The primary storm types are straight-line winds, down-slope winds, thunderstorms, downbursts, northeasters (nor'easters), hurricanes, and tornadoes. For information on these storm types, refer to Section 3.1.1 in FEMA 543.[4]

Of all the storm types, hurricanes have the greatest potential for devastating a large geographical area and, hence, affect the greatest number of people. See Figure 6-2 for hurricane-prone regions.

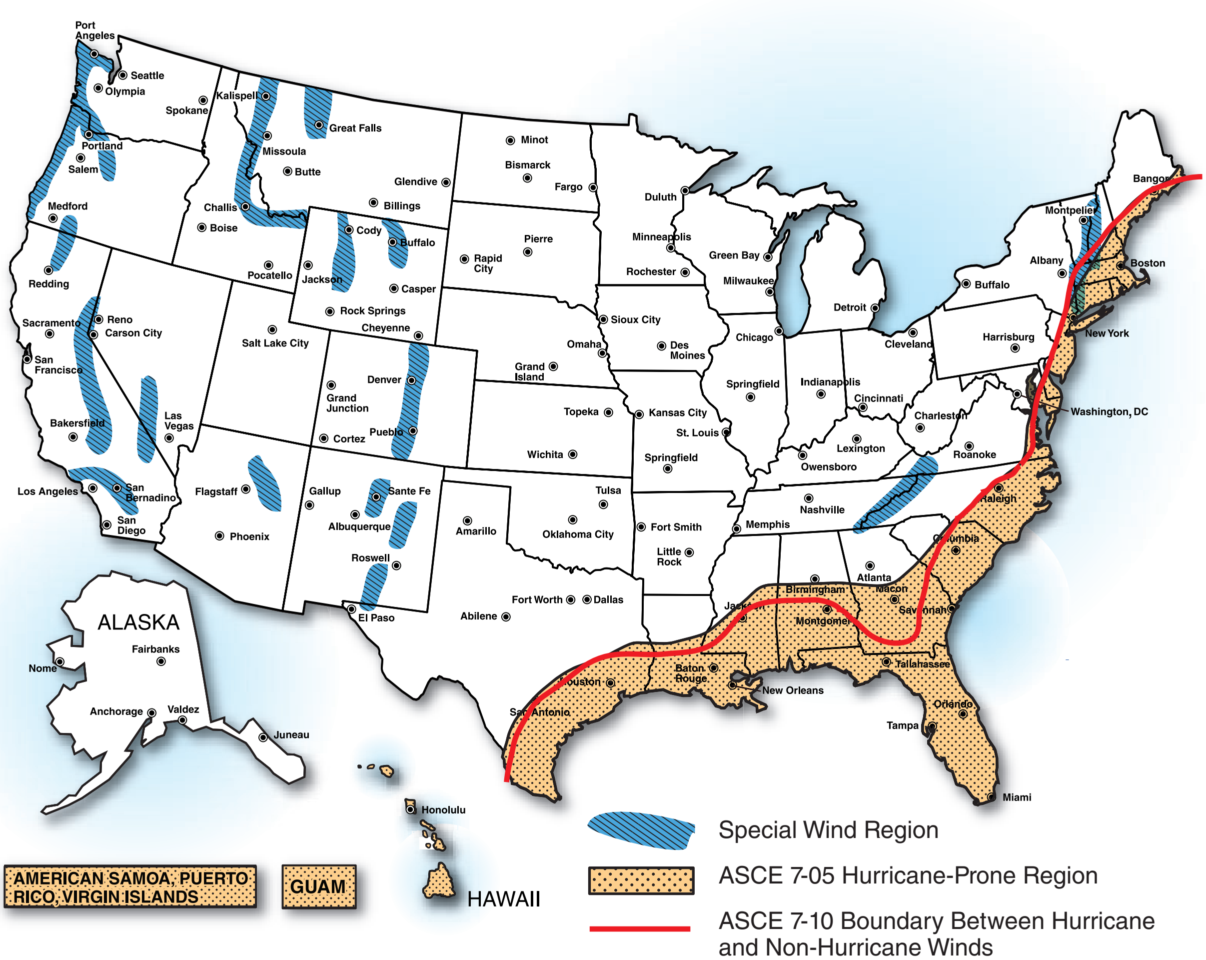


Figure 6-2: Hurricane-prone regions and special wind regions

SOURCE: ADAPTED FROM ASCE 7-10

4 Available at the FEMA Web site. See www.fema.gov/library/viewRecord.do?id=2441

6.1.2 Probability of Occurrence

When designing a school, design professionals should consider the following types of winds:

Routine winds: In many locations, winds with low to moderate speeds occur daily. Damage is not expected to occur during these events.

Stronger winds: At a given site, stronger winds (i.e., winds with a speed in the range of 70- to 80-mph peak gust, measured at 33 feet in Exposure C—refer to Section 6.1.3) may occur from several times a year to only once a year or even less frequently. This is the threshold at which damage normally begins to occur to building elements that have limited wind resistance due to problems associated with inadequate design, insufficient strength, poor installation, or material deterioration.

Design level winds: At a given site, the probability of design level winds occurring in a given year is very low. Schools exposed to design level events and events that are somewhat in excess of design level should experience little, if any, damage. Actual storm history, however, has shown that design level storms frequently cause extensive building envelope damage. Structural damage also occurs, but less frequently. Damage incurred in design level events is typically associated with inadequate design, poor installation, or material deterioration. The exceptions are wind-driven water infiltration and wind-borne debris (missiles) damage. Water infiltration is discussed in Sections 6.3.3.1, 6.3.3.2, and 6.3.3.4.

Tornadoes: Although more than 1,200 tornadoes typically occur each year in the United States, the probability of a tornado occurring at any given location is quite small. The probability of occurrence is a function of location. As described in Section 6.5, only a few areas of the country frequently experience tornadoes, and tornadoes are very rare in the west. Figure 6-3 shows the top 20 tornado-prone States in the United States. The Oklahoma City area is the most active location, with 123 recorded tornadoes between 1890 and 2008 (Edwards, 2009). Well-designed, constructed, and maintained schools should experience little if any damage from weak tornadoes, except for window breakage. However, weak tornadoes often cause building envelope damage because of wind-resistance deficiencies. Most schools experience significant damage if they are in the path of a strong or violent tornado because they typically are not designed for this type of storm.

Missile damage is very common during hurricanes and tornadoes. Missiles can puncture roof coverings, many types of exterior walls, and glazing. The IBC does not address missile-induced damage, except for glazing in wind-borne debris regions. (Wind-borne debris regions are limited to portions of hurricane-prone regions.) In hurricane-prone regions, significant missile-induced building damage should be expected, even during design level hurricane events, unless special enhancements are incorporated into the building's design (discussed in Section 6.3).

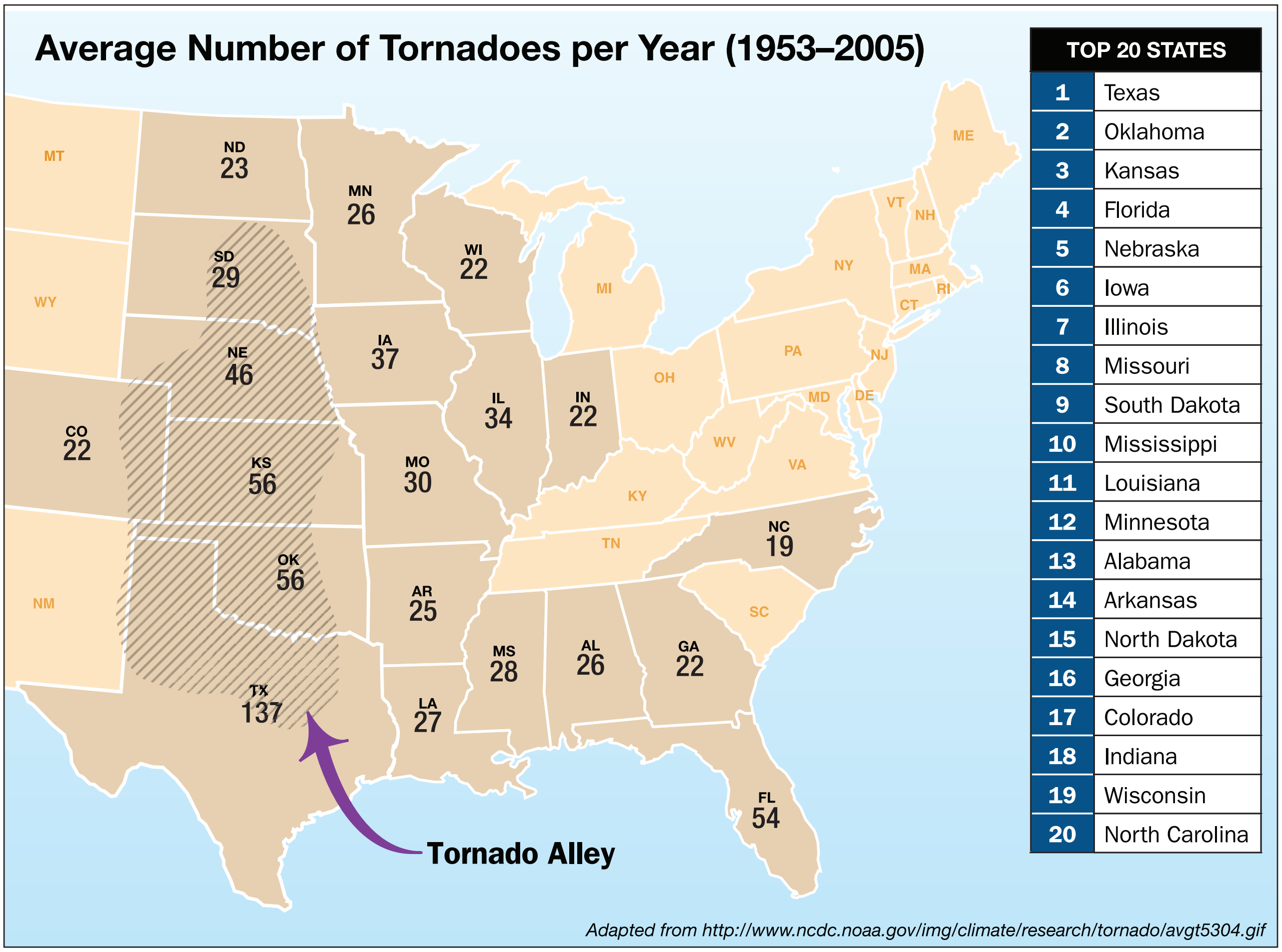


Figure 6-3: Average number of tornadoes per year (1953–2005)

In the classroom wing shown in Figure 6-4, all of the exterior windows were broken, and virtually all of the cementitious wood-fiber deck panels were blown away during a tornado. Much of the metal decking over the band and chorus area also blew off. The gymnasium collapsed, as did a portion of the multi-purpose room. The school was not in session at the time the tornado struck. See Section 6.5 for recommendations pertaining to tornadoes.

Figure 6-4:
This high school was damaged by a strong tornado (Plainfield, IL 1990)

6.1.3 Wind/Building Interactions

When wind interacts with a building, both positive and negative (i.e., suction) pressures occur simultaneously. Schools must have sufficient strength to resist the applied loads from these pressures to prevent wind-induced building failure. Loads exerted on the building envelope are transferred to the structural system, where in turn they must be transferred through the foundation into the ground. The magnitude of the pressures is a function of the following primary factors: exposure, basic wind speed, topography, building height, internal pressure, and building shape. General information on exposure and basic wind speed is presented below. For general information on topography, building height, and internal pressure, refer to Section 3.1.3 in FEMA 543. A description of key issues follows.

> In the 2005 and earlier editions of ASCE 7, Exposure C included areas adjacent to water surfaces in hurricane-prone regions because earlier research indicated that wave conditions generated by hurricanes resulted in roughness that approximated Exposure C conditions. However, subsequent research showed that the surface roughness over the ocean during a hurricane is consistent with that of Exposure D. Consequently, the 2010 edition of ASCE 7 requires use of Exposure D along the hurricane coastline.

ASCE 7 specifies procedures for calculating wind pressures and forces based on the primary factors listed above. The IBC refers to ASCE 7 for wind load determination.

Exposure: The characteristics of the terrain (i.e., ground roughness and surface irregularities in the vicinity of a building) influence the wind loading. ASCE 7 defines three exposure categories, Exposures B, C, and D. Exposure B is the roughest terrain category and Exposure D is the smoothest. Exposure B includes urban, suburban, and wooded areas. Exposure C includes flat open terrain with scattered obstructions and grasslands. Exposure D includes areas adjacent to water surfaces, mud flats, salt flats, and unbroken ice.

For additional exposure information, see the Commentary of ASCE 7, which includes several aerial photographs that illustrate the different terrain conditions associated with Exposures B, C, and D.

The smoother the terrain, the greater the wind load; therefore, schools (with the same basic wind speed) located in Exposure D would receive higher wind loads than those located in Exposure C.

Wind speed: ASCE 7 specifies the basic (design) wind speed for determining design wind loads. The basic wind speed is measured at 33 feet above grade in Exposure C (flat open terrain). If the building is located in Exposure B or D, rather than C, an adjustment for the actual exposure is made in the ASCE 7 calculation procedure.

Although the ASCE 7-10 maps provide strength design wind speeds, for the design of hurricane and tornado safe rooms/shelters, the design wind speeds given in FEMA 361 and ICC 500 are recommended (see Section 6.5). The FEMA 361 and ICC 500 speeds are based on a much greater mean recurrence interval than the ASCE 7 speeds.

Since the 1995 edition of ASCE 7, the basic wind speed measurement has been a 3-second peak gust speed. Prior to that time, the basic wind speed was a fastest-mile speed (i.e., the speed averaged over the time required for a mile-long column of air to pass a fixed point). Because the measuring time for peak gust versus fastest-mile is different, peak gust speeds are greater than fastest-mile speeds.

Because the ASCE 7-10 maps are strength design wind speeds, the speeds are substantially greater than the speeds given in the 2005 and earlier editions. However, because of the load factor change, pressures calculated in accordance with the 2010 edition should be similar to those calculated in accordance with the 2005 edition.

Refer to Section 5.1.6.4 for a discussion of Risk Category III and IV.

Applied Technology Council wind speed Web site: A site-specific basic wind speed can be obtained at the following Web site by entering the site location. The Web site provides speeds based on ASCE 7-93, 7-05, and 7-10. http://windspeed.atcouncil.org

In the 2005 and earlier editions of ASCE 7, one map was used to determine the basic wind speed. However, in the 2010 edition of ASCE 7, three maps based on building risk provide the basic wind speed. One map is for Risk Category I buildings, another for Risk Category II buildings, and another for Risk Category III and IV buildings. All three are strength design wind speed maps. Hence, a load factor of 1.0 is used, rather than 1.6 as used in the 2005 edition. To account for the degree of hazard to human life and damage to property, the 2005 and earlier editions of ASCE 7 used an importance factor in the load calculation equation. In the 2010 edition, the importance factor was eliminated because the degree of hazard to human life and property damage is accounted for by the wind speeds in the appropriate map. Figure 6-5 shows the map for Risk Category III and IV, which as discussed in Section 6.3.1.2 are the Categories that this manual recommends for all schools.

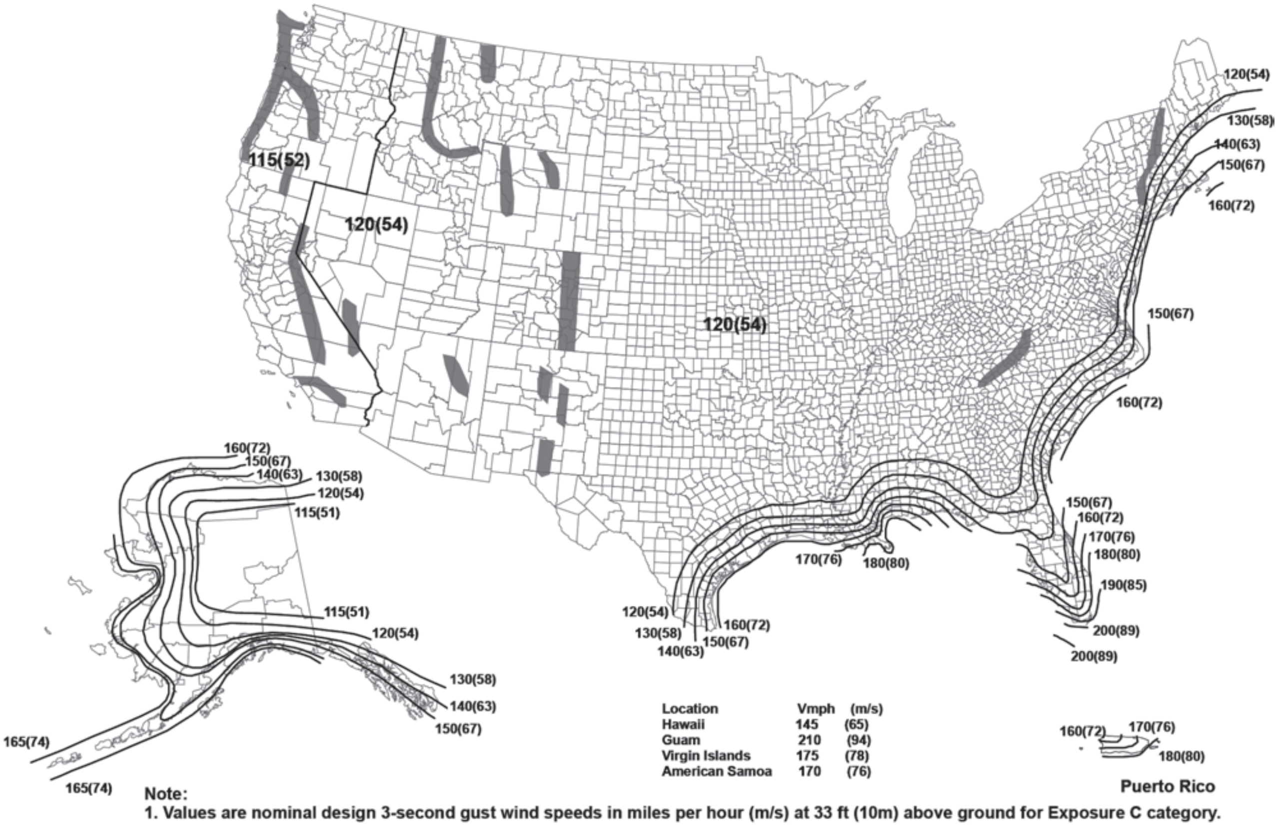


Figure 6-5: Basic wind speeds for Risk Category III and IV buildings and other structures

SOURCE: ASCE 7-10

As shown on Figure 6-5, for Risk Category III and IV buildings, most of the United States has a basic wind speed (peak gust) of 120 mph, but much higher speeds occur in Alaska and in hurricane-prone regions. The highest speed, 210 mph, occurs in Guam.

Hurricane-prone regions include Atlantic and Gulf coastal areas (where the basic wind speed is greater than 120 mph on the map shown in Figure 6-5), Hawaii, and the U.S. territories in the Caribbean and South Pacific. The boundary of the Atlantic and Gulf coast hurricane-prone region shifted towards the coast in the 2010 edition of ASCE 7 because of improvements in the hurricane simulation model (see Figure 6-2).

> The MWFRS is an assemblage of structural elements assigned to provide support and stability for the overall structure. The system generally receives wind loading from more than one surface. The C&C are elements of the building envelope that do not qualify as part of the main wind-force resisting system.

In the ASCE 7 formula for determining wind pressures, the basic wind speed is squared. Therefore, as the wind speed increases, the pressures are exponentially increased, as illustrated in Figure 6-6. This figure also illustrates the relative difference in pressures exerted on the main wind-force resisting system (MWFRS) and the components and cladding (C&C) elements.

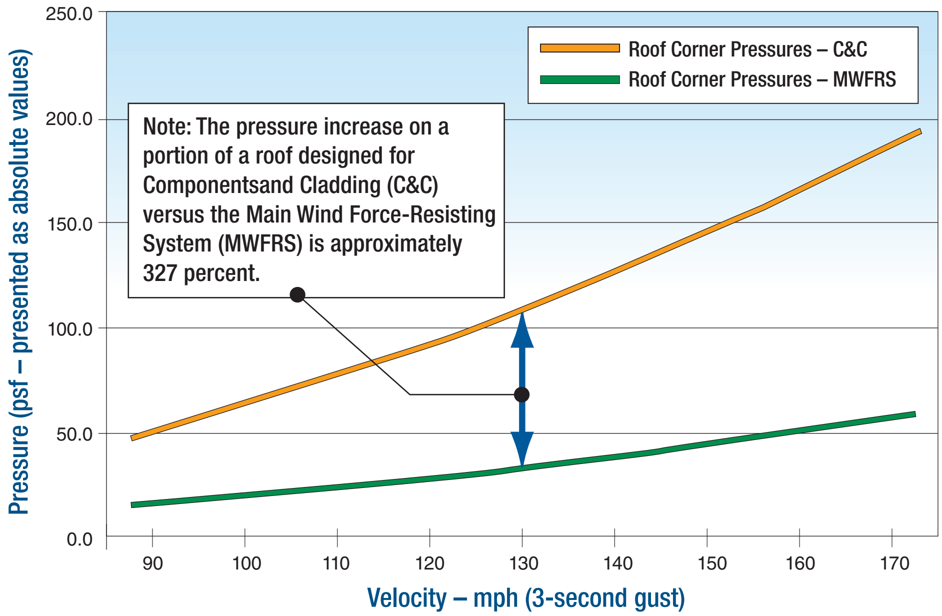


Figure 6-6: Wind pressure as a function of wind speed

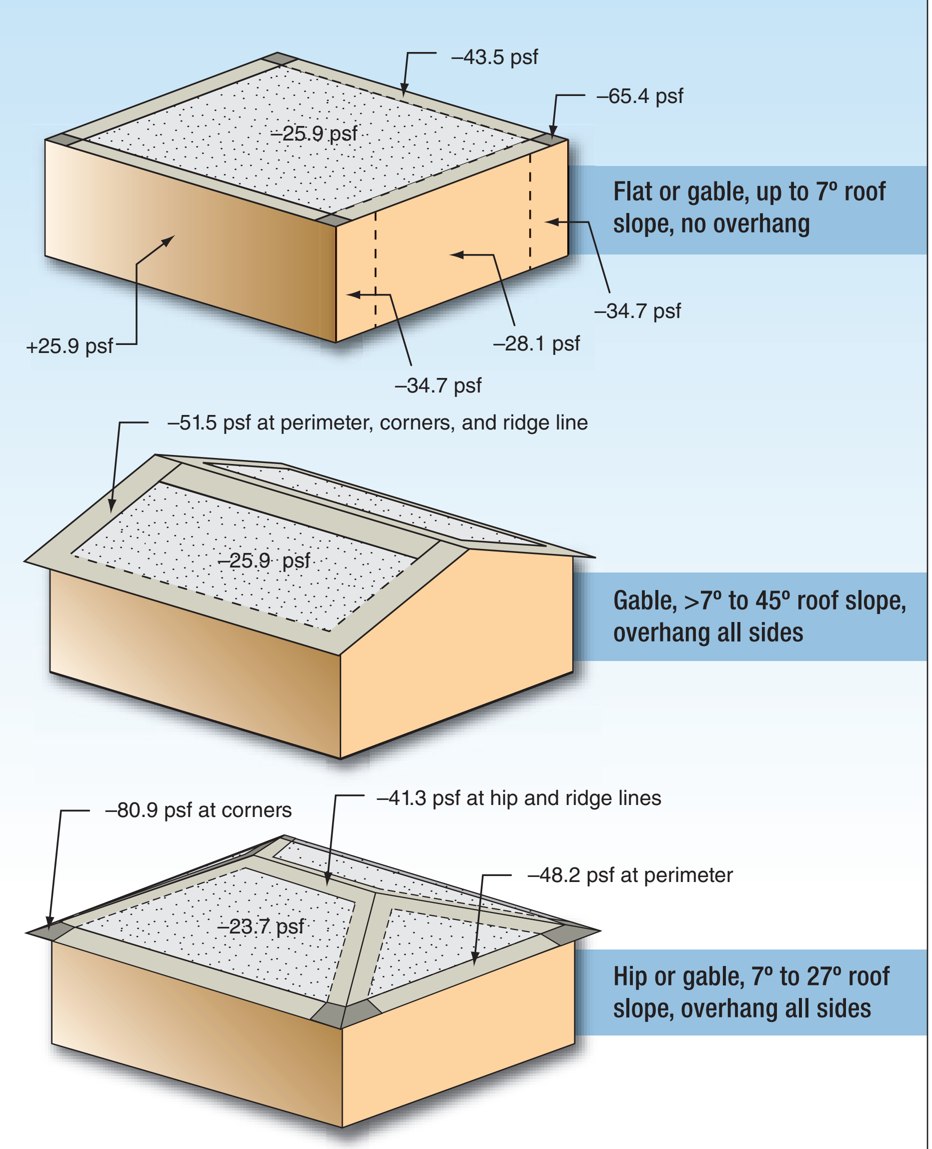
Building shape: The highest uplift pressures occur at roof corners because of building aerodynamics (i.e., the interaction between the wind and the building). The roof perimeter has a somewhat lower load compared to the corners, and the field of the roof has still lower loads. Exterior walls typically have lower loads than the roof. The ends (edges) of walls have higher suction loads than the portion of wall between the ends. However, when the wall is loaded with positive pressure, the entire wall is uniformly loaded. Figure 6-7 illustrates these aerodynamic influences. The negative values shown in Figure 6-7 indicate suction pressure acting upward from the roof surface and outward from the wall surface. Positive values indicate positive pressure acting inward on the wall surface.

Aerodynamic influences are accounted for by using external pressure coefficients in load calculations. The value of the coefficient is a function of the location on the building (e.g., roof corner or field of roof) and building shape as discussed below. Positive coefficients represent a positive (inward-acting) pressure, and negative coefficients represent negative (outward-acting [suction]) pressure. External pressure coefficients for MWFRS and C&C are listed in ASCE 7.

Building shape affects the value of pressure coefficients and, therefore, the loads applied to the various building surfaces. For example, the uplift loads on a low-slope roof are larger than the loads on a gable or hip roof. The steeper the slope, the lower the uplift load. Pressure coefficients for monoslope (shed) roofs, sawtooth roofs, and domes are all different from those for low-slope and gable/hip roofs.

Building irregularities, such as re-entrant corners, bay window projections, a stair tower projecting out from the main wall, dormers, and chimneys can cause localized turbulence. Turbulence causes wind speed-up, which increases the wind loads in the vicinity of the building irregularity, as shown in Figures 6-8 and 6-9. Figure 6-8 shows the aggregate ballast on a building's single-ply membrane roof blown away at the re-entrant corner and in the vicinity of the corners of the wall projections at the window bays. The irregular wall surface created turbulence, which led to wind speed-up and loss of aggregate in the turbulent flow areas.

Figure 6-7: Relative roof uplift pressures as a function of roof geometry, roof slope, and location on roof, and relative positive and negative wall pressures as a function of location along the wall



Note: Design pressures all assume an enclosed Category III or IV building with the same basic wind speed of 120 mph, exposure B, and 30' roof height, based on ASCE 7-10.

Figure 6-8: Aggregate blow-off associated with building irregularities. Hurricane Hugo (South Carolina, 1989)

Figure 6-9: The irregularity created by the stair tower (covered with a metal roof) caused turbulence resulting in wind speed-up and roof damage. Hurricane Andrew (Florida, 1992)

Figure 6-9 shows a building stair tower that caused turbulence resulting in wind speed-up. The speed-up increased the suction pressure on the base flashing along the parapet behind the stair tower. The built-up roof's base flashing was pulled out from underneath the coping because its attachment was insufficient to resist the suction pressure. The base flashing failure propagated and caused a large area of the roof membrane to lift and peel. Some of the wall covering on the stair tower was also blown away. Had the stair tower not existed, the built-up roof would likely not have been damaged. To avoid damage in the vicinity of building irregularities, attention needs to be given to the attachment of building elements located in turbulent flow areas.

Information pertaining to load calculations is presented in Section 6.3.1.2. For further general information on the nature of wind and wind-building interactions, see *Buildings at Risk: Wind Design Basics for Practicing Architects* (American Institute of Architects, 1997).

To avoid the roof membrane damage shown in Figure 6-9, it would be prudent to use corner uplift loads in lieu of perimeter uplift loads in the vicinity of the stair tower, as illustrated in Figure 6-10. Wind load increases due to building irregularities can be identified by wind tunnel studies; however, wind tunnel studies are rarely performed for schools. Therefore, identification of wind load increases due to building irregularities is normally based on the designer's professional judgment. Usually load increases only need to be applied to the building envelope, and not to the MWFRS.

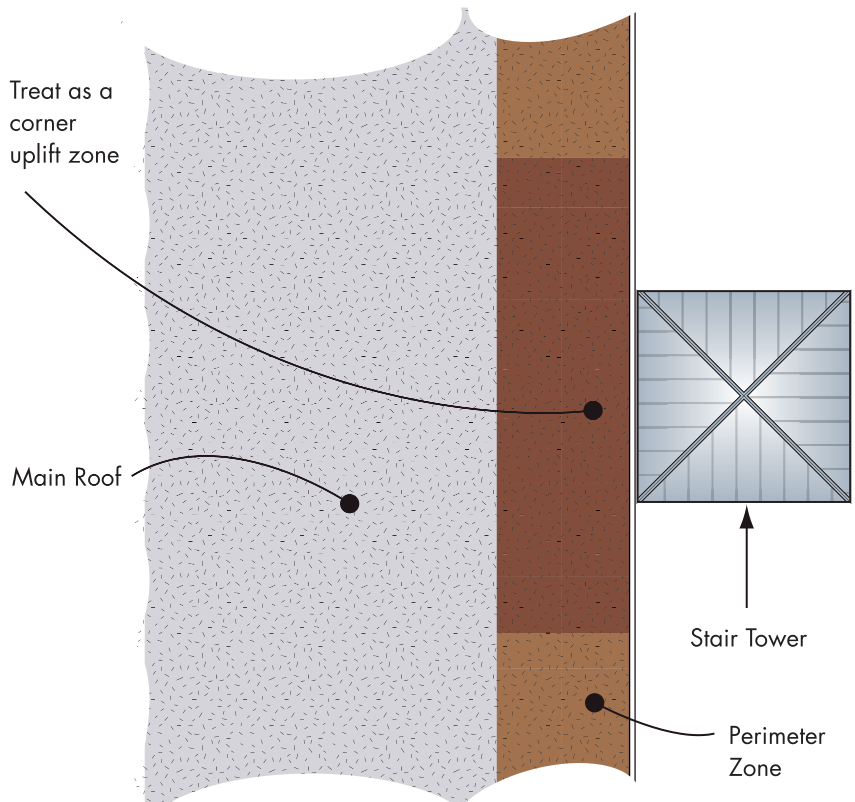


Figure 6-10: Plan view of a portion of the building in Figure 6-9 showing the use of a corner uplift zone in lieu of a perimeter uplift zone on the low-slope roof in the vicinity of the stair tower

6.1.4 Building Codes

The IBC is the most extensively used model code. However, in some jurisdictions, one of the earlier model building codes, or a specially written State or local building code, may be used. The specific scope and/or effectiveness and limitations of these other building codes are somewhat different from those of the IBC. It is incumbent upon the design professionals to be aware of the specific code (including the edition of the code and local amendments) that has been adopted by the authority having jurisdiction over the location of the school.

6.1.4.1 Scope of Building Codes

With respect to wind performance, the scope of the model building codes has greatly expanded since the mid-1980s. Some of the most significant improvements are discussed below.

Recognition of increased uplift loads at the roof perimeter and corners: Prior to the 1982 edition of the Standard Building Code (SBC) and the Uniform Building Code (UBC), and the 1987 edition of the National Building Code (NBC), these model codes did not account for the increased uplift at the roof perimeter and corners. Therefore, schools designed in accordance with earlier editions of these codes are very susceptible to blow-off of the roof deck and/or roof covering.

Adoption of ASCE 7 for design wind loads: Although the SBC, UBC, and NBC permitted use of ASCE 7, the 2000 edition of the IBC was the first model code to require ASCE 7 for determining wind design loads on all buildings. ASCE 7 has been more reflective of the current state of the knowledge than the earlier model codes, and use of this procedure typically has resulted in higher design loads.

Roof coverings: Several performance and prescriptive requirements pertaining to wind resistance of roof coverings have been incorporated into the model codes. The majority of these additional provisions were added after Hurricanes Hugo (1989) and Andrew (1992). Poor performance of roof coverings was widespread in both of those storms. Prior to the 1991 edition of the SBC and UBC, and the 1990 edition of the NBC, these model codes were essentially silent on roof covering wind loads and test methods for determining uplift resistance. Code improvements continued to be made through the 2006 edition of the IBC, which added a provision that prohibits aggregate roof surfaces in hurricane-prone regions.

Glazing protection: The 2000 edition of the IBC was the first model code to address wind-borne debris (missile) requirements for glazing in buildings located in hurricane-prone regions (via reference to the 1998 edition of ASCE 7). The 1995 edition of ASCE 7 was the first edition to address wind-borne debris requirements.

> ASCE 7 requires impact-resistant glazing in wind-borne debris regions within hurricane-prone regions. Impact-resistant glazing can either be laminated glass, polycarbonate, or shutters tested in accordance with standards specified in ASCE 7. The wind-borne debris load criteria were developed to minimize property damage and to improve building performance. The criteria were not developed for occupant protection. Where occupant protection is a specific criterion, the more conservative wind-borne debris criterion given in FEMA 361, *Design and Construction Guidance for Community Shelters*, is recommended.

Parapets and rooftop equipment: The 2003 edition of the IBC was the first model code to address wind loads on parapets and rooftop equipment (via reference to the 2002 edition of ASCE 7, which was the first edition of ASCE 7 to address these elements).

High-wind shelters: The 2009 edition of the IBC was the first model code to adopt the new ICC 500. See Section 6.5 for further discussion of ICC 500.

6.1.4.2 Effectiveness and Limitations of Building Codes

A key element of an effective building code is for a community to have an effective building department. Building safety depends on more than the codes and the standards they reference. Building safety results when trained professionals have the resources and ongoing support they need to stay on top of the latest advancements in building safety. An effective building safety system provides uniform code interpretations, product evaluations, and professional development and certification for inspectors and plan reviewers. Local building departments play an important role in helping to ensure buildings are designed and constructed in accordance with the applicable building codes. Meaningful plan review and inspection by the building department are particularly important for schools.

General limitations to building codes include the following:

- Because codes are adopted and enforced on the local or State level, the authority having jurisdiction has the power to eliminate or modify wind-related provisions of a model code, or write its own code instead. In places where important wind-related provisions of the current model code are not adopted and enforced, schools are more susceptible to wind damage. Additionally, a significant time lag often exists between the time a model code is updated and the time it is implemented by the authority having jurisdiction. Buildings designed to the minimum requirements of an outdated code are, therefore, not taking advantage of the current state of the knowledge. These buildings are prone to poorer wind performance compared to buildings designed according to the current model code.
- Adopting the current model code alone does not ensure good wind performance. The code is a minimum that should be used by knowledgeable design professionals in conjunction with their training, skills, professional judgment, and the best practices presented in this manual. To achieve good wind performance, in addition to good design, the construction work must be effectively executed, and the building must be adequately maintained and repaired.
- Schools need to perform at a higher level than required by codes and standards.

IBC 2009: The 2009 edition of the IBC is believed to be a relatively effective code, provided that it is properly followed and enforced. However, with respect to hurricanes, the IBC provisions pertaining to building envelopes and rooftop equipment do not adequately address the special needs of schools. For example, the following is a list of items that need to be addressed through the use of best practices:

- They do not account for water infiltration due to puncture of the roof membrane by missiles (see Figure 6-11)
- They do not adequately address the vulnerabilities of brittle roof coverings (such as tile) to missile-induced damage and subsequent progressive failure
- For schools used as hurricane recovery centers after a hurricane, they do not account for interruption of water or sewer service or prolonged interruption of electrical power.

Figure 6-11: The single-ply roof membrane on this school was torn by a missile. The tear was still unprotected 6 days after it was damaged. A substantial amount of water can enter the building through such a tear, unless the deck is water tight (see Figure 6-13) or a secondary roof membrane is used as discussed in Section 6.3.3.7. Estimated wind speed: 105 to 115 mph. Hurricane Ivan (Florida, 2004)

Addressing the first two elements is important for ensuring that the buildings are in suitable condition for school to resume within a couple of weeks after a hurricane. The last element is important for schools that will be used for recovery centers. Guidance for addressing these elements where they are not adequately addressed in IBC is provided in Sections 6.3 and 6.4.

- The 2000, 2003, 2006, and 2009 IBC rely on several referenced standards and test methods developed or updated in the last two decades. Prior to adoption, most of these standards and test methods had not been validated by actual building performance during design level wind events. The hurricanes of 2004, 2005, and 2008 provided an opportunity to evaluate the actual performance of buildings designed and constructed to the minimum provisions of the IBC. Building performance evaluations conducted by FEMA revealed the need for further enhancements to the 2009 IBC pertaining to some of the test methods used to assess wind and wind-driven rain resistance of building envelope components. For example, there is no test method to assess wind resistance of gutters. Further, the test method to evaluate the resistance of windows to wind-driven rain is inadequate for high wind events. However, before testing limitations can be overcome, research needs to be conducted, new test methods need to be developed, and some existing test methods need to be modified. Guidance to address shortcomings in standards and test methods is provided in Sections 6.3 and 6.4.
- The 2009 IBC Section 1614 is a new provision that addresses structural integrity (i.e., requirements for continuity, redundancy, or energy-dissipating capability [ductility] to limit the effects of local collapse, and to prevent or minimize progressive collapse after the loss of one or two primary structural members, such as a column). However, the Section only pertains to Category III and IV high-rise buildings. Although schools are not required to comply with this Section, this manual recommends that school designers consider the criteria in Section 1614.
- Except for storm shelters, the 2009 IBC does not account for tornadoes; therefore, except for weak tornadoes, it is ineffective for this type of storm.[5] Guidance to overcome this shortcoming is given in Section 6.5.

5 Except for glass breakage, code-compliant buildings should not experience significant damage during weak tornadoes.

6.2 Schools Exposed to High Winds

6.2.1 Vulnerability: What High Winds Can Do to Schools

This section provides an overview of the common types of wind damage and their ramifications.

6.2.1.1 Types of Building Damage

When damaged by wind, schools typically experience a variety of building component damage. For example, at the school shown in Figure 6-12, the roof covering was severely damaged, metal wall panels were blown off, and rooftop equipment was blown away. Water entered the building at all of these envelope breaches. The most common types of damage are discussed below in descending order of frequency.

Figure 6-12: Constructed in 1995, this school was used as a hurricane shelter. The large number of occupants moved from one area of the school to another as water entered various areas of the building due to envelope failures. Estimated wind speed: 105 to 115 mph. Hurricane Ivan (Florida, 2004)

Roof: Roof covering damage (including rooftop mechanical, electrical, and communications equipment) is the most common type of wind damage, as illustrated by Figure 6-13. At this school, a portion of the built-up membrane lifted and peeled after the metal edge flashing lifted. The cast-in-place concrete deck kept most of the water from entering the building. Virtually all of the loose aggregate blew off the roof and broke many windows in nearby houses. This school was used as a hurricane shelter at the time of the blow-off.

Figure 6-13:
Extensive roof covering and rooftop equipment damage occurred on this school. However, the cast-in-place concrete deck kept most of the water from entering the school. Hurricane Andrew (Florida, 1992)

Glazing: Exterior glazing damage is very common during hurricanes and tornadoes, but is less common during other storms. The glass shown in Figure 6-14 was broken by the aggregate from a built-up roof. The inner panes had several impact craters. In several of the adjacent windows, both the outer and inner panes were broken. The aggregate flew more than 245 feet.

Figure 6-14:
The outer window panes were broken by aggregate from a built-up roof. Estimated wind speed: 104 mph. Hurricane Hugo (South Carolina, 1989)

Wall coverings, soffits, and large doors: Exterior wall covering, soffit, and large door damage is common during hurricanes and tornadoes, but is less common during other storms. At the school shown in Figure 6-15, metal wall panels were blown off the gable end wall, thereby allowing wind-driven rain to enter the building.

Wall collapse: Collapse of non-load-bearing exterior walls is common during tornadoes, but is less common during other storms. At the school shown in Figure 6-16, the unreinforced CMU wall collapsed during a hurricane.

Figure 6-15: Blow-off of metal wall panels allowed wind-driven rain to enter this school. Hurricane Frances (Florida, 2004)

Figure 6-16: Collapsed unreinforced CMU wall. Hurricane Marilyn (U.S. Virgin Islands, 1995)

Structural system: Structural damage (e.g., roof deck blow-off, blow-off or collapse of the roof structure, collapse of exterior bearing walls, or collapse of the entire building or major portions thereof) is the principal type of damage that occurs during strong and violent tornadoes (see Figure 6-17). Structural damage occasionally occurs during hurricanes (Figures 6-18, 6-21, 6-24, 6-26, and 6-34). Portable classrooms are also sometimes severely damaged or overturned as shown in Figure 6-19.

Figure 6-17: The roof and all of the walls of a wing of this elementary school were blown away by a violent tornado. (Oklahoma City, 1999)

Figure 6-18: This elementary school was composed of several buildings. The building in the foreground collapsed and several others experienced significant structural damage. The buildings further up the hillside are residences. Hurricane Marilyn (U.S. Virgin Islands, 1995)

Figure 6-19:
This portable classroom was blown up against the main school building. Depending upon the type of exterior wall, an impacting portable classroom may or may not cause wall collapse. Hurricane Marilyn (U.S. Virgin Islands, 1995)

6.2.1.2 Ramification of Damage

The ramifications of building component damage on schools are described below.

Property damage: Property damage requires repairing/replacing the damaged components (or replacing the entire facility), and may require repairing/replacing interior building components, furniture, and other equipment, books, and mold remediation. As illustrated by Figures 6-11, 6-12, 6-13, and 6-20, even when damage to the building envelope is limited, such as blow-off of a portion of the roof or wall covering or broken glazing, substantial water damage frequently occurs because heavy rains often accompany strong winds (particularly in the case of thunderstorms, tropical storms, hurricanes, and tornadoes).

Wind-borne debris such as roof aggregate, gutters, rooftop equipment, and siding blown from buildings can damage vehicles and other buildings in the vicinity. Debris can travel well over 300 feet in high-wind events.

Ancillary buildings (such as storage or shop buildings) adjacent to schools are also vulnerable to damage. Although loss of these buildings may not be crippling to the operation of the school, debris from ancillary buildings may strike and damage the school (Figure 6-21).

Modest wind speeds can drive rain into exterior walls. Unless adequate provisions are taken to account for water infiltration (see Sections 6.3.3.1–6.3.3.5), damaging corrosion, dry rot, and mold can occur within the walls.

Figure 6-20: This newly-constructed gymnasium had a structural metal roof panel (3-inch trapezoidal ribs at 24 inches on center) applied over metal purlins. The panels detached from their concealed clips. A massive quantity of water entered the school and buckled the wood gym floor. Typhoon Paka (Guam, 1997)

Figure 6-21: The entire metal deck and steel joist roof structure at this school's auto shop blew off. Estimated wind speed: 105 to 115 mph. Hurricane Ivan (Florida, 2004)

Portable classrooms are often particularly vulnerable to significant damage because they are seldom designed to the same wind loads as permanent school buildings. Portable classrooms are frequently blown over during high-wind events because of the inexpensive techniques typically used are inadequate to anchor the units to the ground (see Figures 6-19 and 6-22). Wind-borne debris from portables or an entire portable classroom may impact the permanent school building and cause serious damage (Figure 6-19).

Figure 6-22: The metal straps between this portable classroom and the ground anchors were not taut. This classroom is susceptible to being blown off the piers and to overturning. See Figure 6-27 for a robust anchoring system.

Injury or death: Although infrequent, school occupants or people outside schools have been injured and killed when struck by collapsed building components (such as exterior masonry walls or the roof structure) or wind-borne debris. The greatest risk of injury or death is during strong hurricanes and strong/violent tornadoes. The old school shown in Figure 6-23 was used as a hurricane shelter, even though it was not originally designed or subsequently retrofitted (i.e., mitigated) to serve as a shelter. The roof structure was composed of cementitious wood-fiber panels over steel joists. In the era when this building was constructed, these types of panels typically had very limited uplift resistance in perimeter and corner areas. Also, steel joists in that era typically offered limited uplift resistance. Structural failure was avoided not because of the strength of the building, but rather, because winds at the site were not as strong as they reasonably could have been expected to be.

People are not usually outside a school during hurricanes. However, when schools are used as hurricane shelters, it is common for people to arrive at schools during very high winds. Missiles such as roof aggregate or tile shedding from a school could injure or kill late arrivals to the shelter.

Also, students arriving at or departing from a school could be vulnerable. A 1967 tornado killed 13 students at the Belvedere High School in northern Illinois and seriously injured many others. School had been dismissed shortly before the tornado struck and many students were in school buses as the tornado approached the school. Although an attempt was made to get the students back inside the school, 12 of the buses were thrown about by the tornado before the students could seek shelter within the school. Aggregate from the school's built-up roof penetrated the flesh of several students.

Figure 6-23: This old school was used as a hurricane shelter. Structural failure did not occur during this hurricane. However, portions of the roof covering were blown off, rooftop equipment was damaged, and many windows were broken by aggregate from the built-up roof (red arrow). Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

Interrupted use: Depending upon the magnitude of wind and water damage, it can take days, months, or more than a year to repair the damage or replace a facility (see Figure 6-24). In addition to the costs associated with repairing/replacing the damage, other social and financial costs can be even more significant. Additional costs related to interrupted use of schools can include the cost of bussing students to alternative schools and/or rental of temporary facilities, and can be quite substantial.

There are also social and psychological factors, such as difficulties imposed on students, parents, faculty, and the administration during the time the school is not usable.

Figure 6-24:
A portion of the roof structure blew off this school, and a portion of it collapsed into classrooms. Extensive water damage can cause such a school to be out of operation for a considerable period of time. Hurricane Marilyn (U.S. Virgin Islands, 1995)

6.2.2 Priorities, Costs, And Benefits: New Schools

Priorities, costs, and benefits of potential risk reduction measures should be evaluated before beginning the risk reduction design process. These factors, as discussed below, should be considered within the context of performance-based wind design as discussed in Section 2.7.

6.2.2.1 Priorities

The first priority in risk reduction is the implementation of measures that will reduce risk of casualties to students, faculty, staff, and visitors. The second priority is the reduction of damage that leads to downtime and disruption. The third priority is the reduction of damage and repair costs. To realize these priorities, the school should be designed and constructed, as a minimum, in accordance with the latest edition of a current model building code such as the IBC unless the local building code has more conservative wind-related provisions, in which case the local building code should be used as the basis for design. In addition, the school should be adequately maintained and repaired.

The benefit-cost ratio of incorporating specially designed tornado safe rooms within schools can be assessed using software that accompanies the FEMA BCA Toolkit and the FEMA BCA Software (version 4.5.4). Tornado shelters have been constructed in several schools in Kansas, Oklahoma, and a few other States. An architect involved with several of the Kansas schools reports that the additional cost to incorporate a shelter ranges from about $40.50 to $51.50 per square foot (psf) of shelter space (year 2010 costs). Oftentimes as the safe room is small compared to the entire school, this results in only a 1 to 3 percent increase to total project cost. FEMA 361 recommends using a minimum of 5 square feet per person for sheltering; therefore, the $40.50 to $51.50 psf equates to about $200 to $260 per student and staff for "near absolute protection" (i.e., protection from injury or death) from a violent tornado. Tornado safe rooms and shelters are discussed in Section 6.5.

The increase in costs to construct a safe room for the hurricane hazard has a much more significant variation. This is because of the great variation of basic wind speeds in hurricane-prone regions. Hence, the incremental costs in the highest wind speed areas are much less than the costs in the lower wind speed areas. See FEMA 361, Chapter 2.[7]

For schools that will be used for emergency response after a storm and/or those schools that will be used for hurricane shelters, measures beyond those required by the IBC should be given high priority (see Section 6.5).

For schools located in tornado-prone regions, the incorporation of specially designed occupant shelters within the school (see Section 6.5) should be given priority. The decision to incorporate occupant shelters should be based on the assessment of risk (see Section 6.5).

For schools located in areas where the basic wind speed is greater than 120 mph, the incorporation of design, construction, and maintenance enhancements should be given priority.[6] The degree of priority given to these enhancements increases as the basic wind speed increases (see Step 4: Peer Review in Section 6.3.1.2 and Sections 6.3.2, 6.3.3 and 6.3.4 for enhancement examples).

6.2.2.2 Cost, Budgeting, and Benefits

The cost to comply with the IBC should be considered as the minimum baseline cost.

For schools that will be used for emergency response after a storm and/or schools that will be used for hurricane shelters, the additional cost for implementing measures beyond those required by the 2009 edition of the IBC will typically add only a small percentage to the total cost of construction. Sections 6.3, 6.3.4, 6.4, and 6.5 discuss additional measures that should be considered.

6 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

7 FEMA 361 is a manual for architects and engineers. It presents detailed guidance concerning the design and construction of safe rooms that provide "near-absolute protection" from tornadoes and hurricanes (see Section 6.5 for the distinction between shelters and safe rooms). FEMA 361 discusses safe room location, design loads for wind pressure and wind-borne debris, performance criteria, and human factor criteria. It is accompanied by a benefit-cost model.

For all other schools, the additional cost for implementing enhancements will typically add only a very small percentage to the total cost of construction. Sections 6.3 to 6.4 discuss additional measures that should be considered.

The yearly cost of periodic maintenance and repair is greater than the alternative of not expending any funds for periodic maintenance (i.e., deferred maintenance and repair). The extent and cost of the deferred maintenance and repair is typically much greater over the long term. Also, if a windstorm causes damage that would have otherwise been avoided had maintenance or repairs been performed, the resulting costs can be significantly higher. (Note: Maintenance and repair costs are reduced when more durable materials and systems are used; see Section 6.3.1.2, under Step 3, Durability.)

Budgeting: School districts should give consideration to wind enhancement costs early in the development of a new school project. If enhancements, particularly those associated with schools used as hurricane shelters, for emergency response after a storm, and as tornado shelters, are not included in the initial project budget, often it is very difficult to find funds later during the design of the project. If the additional funds are not found, the enhancements may be eliminated because of lack of forethought and adequate budgeting.

Benefits: If strong storms do not occur during the life of a school, money and effort spent on wind resistance provide little benefit. However, considering the long life of most schools (hence, the greater probability of experiencing a design level event) and the importance of schools to the community, investing in adequate wind resistance is prudent. The potential for loss of life and injuries can be significantly reduced or virtually eliminated. Investing in wind resistance also minimizes future expenditures for repair or replacement of wind-damaged schools and avoids costly interruptions to building use.

Fortunately, most of the enhancements for increased wind resistance are relatively inexpensive compared to the benefits that they provide. Enhancements that provide greater performance reliability at a lower cost should be considered. For the building shown in Figure 6-25, a few inexpensive fasteners would have prevented costly repairs and interrupted use of a portion of the building. After the HVAC unit blew off the roof curb and landed in the parking lot, a substantial amount of water entered the building before a temporary covering could be placed over the opening. The blow-off was caused by a load path discontinuity; no provisions had been made to anchor the unit to the curb. The insignificant cost of a few fasteners would have prevented repairs costing several thousand dollars and also prevented interrupted use of a portion of the building.

Wind resistance enhancements may also result in decreased insurance premiums. School districts should consult their insurer to see if premium reductions are available, and to see if special enhancements are required in order to avoid paying a premium for insurance. For those school districts that self-insure, enhanced wind resistance should result in a reduction of future payouts.

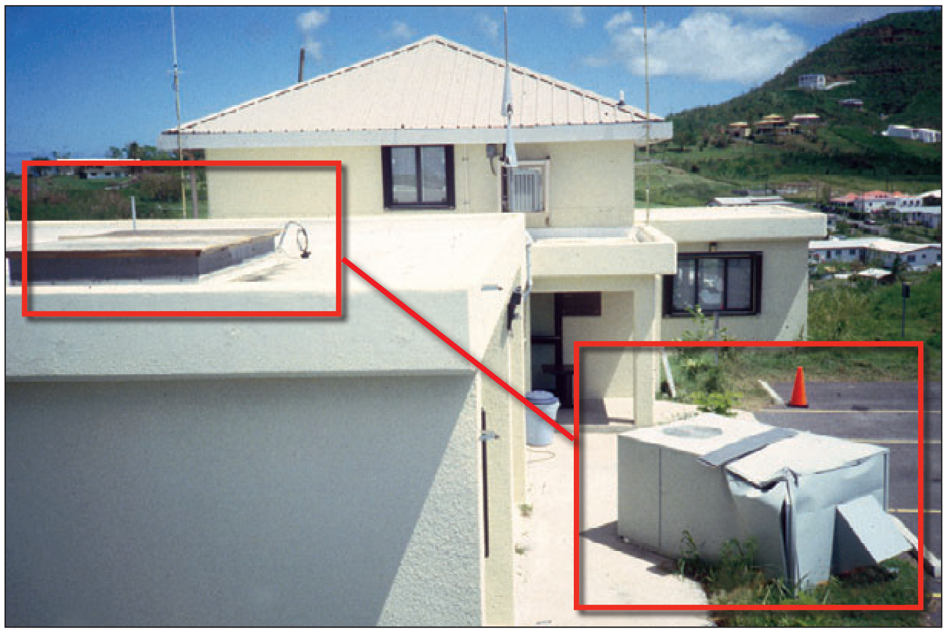


Figure 6-25: Lack of fasteners resulted in blow-off of the HVAC unit, which caused extensive interior water damage and interrupted facility use. Hurricane Marilyn (U.S. Virgin Islands, 1995)

6.2.3 Priorities, Costs, and Benefits: Existing Schools

Priorities, costs, and benefits of potential risk reduction measures should be evaluated before beginning the risk reduction design process. These factors, as discussed below, should be considered within the context of performance-based wind design as discussed in Section 2.7.

6.2.3.1 Priorities

School districts should assess schools for all applicable hazards to determine which schools are vulnerable to damage and most in need of remedial work. The highest priority work may or may not be related to wind. In some instances, the same remedial work may mitigate multiple hazards. For example, strengthening a roof deck attachment can improve both wind and seismic resistance.

School districts located in the following areas (listed in descending order of priority) are at the greatest risk for wind damage: hurricane-prone regions and school districts outside of hurricane-prone regions that have schools that will be used for emergency response after a storm; tornado-prone regions; areas where the basic wind speed is in excess of 120 mph (the priority increases as the basic wind speed increases); and areas where the basic wind speed is 120 mph or less.[8]

For school districts in hurricane-prone regions, schools that will be used as hurricane shelters should be the highest priority. Other priorities are as discussed at the beginning of Section 6.2.2.1. For school districts in tornado-prone regions, occupant protection (see Section 6.5) should be the highest priority. Other priorities are as discussed at the beginning of Section 6.2.2.1. For all other school districts, the priorities are the same as discussed at the beginning of Section 6.2.2.1.

In some instances, all the available funds for remedial work may be spent at one school. In other instances, the available funds may be used for remedial work at several schools.

See Section 6.4 for specific remedial work guidance.

6.2.3.2 Cost, Budgeting, and Benefits

Wind-resistance improvements should ideally address all elements in the load path from the building envelope to the structural system and into the ground (Load path is discussed in Section 6.3.1.2 under Step 3, Detailed Design). However, this approach can be very expensive if there are many inadequacies throughout the load path. The maximum return on investment for wind-resistance improvements is typically for enhancements to the building envelope. Obviously if there are serious structural deficiencies that could lead to collapse during strong storms, these types of deficiencies should receive top priority; however, this scenario is infrequent.

Because elements of the building envelope are the building components most likely to fail in the more common moderate wind speed events, strengthening these elements will avoid damage during those storms. In a storm approaching a design level event, the building envelope will remain attached to the structure, but a structural element may fail. For example, if the connections between the roof joists and bearing walls are the weak link, the roof covering will remain attached to the roof deck and the deck will remain attached to the joists, but the entire roof structure will blow off because the joists will detach from the wall. Although

8 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

loss of the entire roof structure is more catastrophic than the loss of just the roof covering, much stronger events are typically required to cause structural damage. Hence, on a school district-wide level, strengthening building envelopes will likely result in the maximum return for wind-resistance improvements. Of course, for a specific school, the scope of wind-resistance work should be tailored to each school, commensurate with the findings from the hazard assessment (as discussed in Section 6.2.4.2) and the benefit-cost analysis (discussed below).

Costs can be minimized if wind-resistance improvements are executed as part of planned repairs or replacement. For example, if the roof deck is inadequately attached in the perimeter and corners (see Figure 6-26), and the roof covering has another 10 years of remaining service life, it would typically be prudent to postpone performing deck attachment upgrade until it is necessary to replace the roof covering. Then, as part of the reroofing work, the existing roof system could be torn off, the deck reattached or replaced, and the new membrane installed.[9] This approach provides the cost benefit of utilizing the full service life of the roof membrane.

Figure 6-26:
The cementitious wood-fiber deck panels blew off the overhangs and caused a progressive lifting and peeling of the roof membrane. Strengthening (or replacing) inadequately attached roof decks during a reroofing project is both prudent and relatively economical. Estimated wind speed: 120 mph. Hurricane Katrina (Mississippi, 2005)

Budgeting: As with new construction, school districts should give consideration to wind enhancement costs early in the development of a major repair/renovation project (see discussion in Section 6.2.2.2).

9 In some cases, reattaching the decking from below the deck may be more economical, but typically this approach is more costly.

Benefits: The benefits of money and effort spent on wind resistance for existing schools are the same as described for new schools in Section 6.2.2.2.

6.2.4 Evaluating Schools for Risk from High Winds

This section describes the process of hazard risk assessment. Although no formal methodology for risk assessment has been adopted, prior experience provides sufficient knowledge upon which to base a recommended procedure for risk assessment of schools. The procedures presented below establish guidelines for evaluating the risk to new and existing buildings from windstorms other than tornadoes. These evaluations will allow development of a vulnerability assessment that can be used along with the site's wind regime to assess the risk to schools.

In the case of tornadoes, neither the IBC nor ASCE 7 requires buildings (including schools) to be designed to resist tornado forces; nor are occupant shelters required in buildings located in tornado-prone regions.[10] Constructing tornado-resistant schools is extremely expensive because of the extremely high pressures and missile impact loads that tornadoes can generate. Therefore, when consideration is voluntarily given to tornado design, the emphasis is typically on occupant protection, which is achieved by "hardening" portions of a school for use as safe havens. FEMA 361 includes a comprehensive risk assessment procedure that designers can use to assist building owners in determining whether a tornado shelter should be included as part of a new school. See Section 6.5 for recommendations pertaining to best practices for incorporating safe rooms in schools in hurricane- and tornado-prone regions.

6.2.4.1 New Buildings

When designing new schools, a two-step procedure is recommended for evaluating the risk from windstorms (other than tornadoes).

Step 1: Determine the basic wind speed from ASCE 7. As the basic wind speed increases beyond 120 mph, the risk of damage increases.[11] Design, construction, and maintenance enhancements are recommended to compensate for the increased risk of damage (see Section 6.3).

10 The 2009 edition of the IBC references ICC 500 for the design and construction of hurricane and tornado shelters. However, as discussed in Section 6.5, while ICC 500 specifies shelter criteria, it does not require shelters.

11 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

As part of Steps 2 and 3, consider the availability of other schools or buildings in the community that could be used for educational purposes (and emergency response if the school is so designated) in the event that the school is damaged. For example, in an isolated community, the school may be the only facility available for education and/or emergency response, in which case loss of school use would be very serious. In this scenario, the enhancements given in Sections Sections 6.3.1.5, 6.3.2.2, 6.3.3.3, 6.3.3.5, 6.3.3.7, 6.3.4.2, 6.3.4.4, 6.3.5, and 6.3.6 should be followed and some of the enhancements should be even more robust.

Step 2: For schools not located in hurricane-prone regions, determine if the school will be used for emergency response after a storm (e.g., temporary housing, food or clothing distribution, or a place where people can fill out forms for assistance). If so, refer to the design, construction, and maintenance enhancements recommended for schools in hurricane-prone regions (see Sections 6.3.1.5, 6.3.2.2, 6.3.3.3, 6.3.3.5, 6.3.3.7, 6.3.4.2, 6.3.4.4, 6.3.5, and 6.3.6).

Step 3: For schools in hurricane-prone regions, refer to the design, construction, and maintenance enhancements recommended in Sections 6.3.1.5, 6.3.2.2, 6.3.3.3, 6.3.3.5, 6.3.3.7, 6.3.4.2, 6.3.4.4, 6.3.5, and 6.3.6

6.2.4.2 Existing Buildings

The resistance of existing buildings is a function of their original design and construction, various additions or modifications, and the condition of building components (which may have weakened due to deterioration or fatigue). For existing buildings, a two-step procedure for evaluating the risk from windstorms (other than tornadoes) is also recommended.

Step 1: Calculate the wind loads on the building using the current edition of ASCE 7, and compare these loads with the loads for which the building was originally designed. The original design loads may be noted on the contract drawings. If not, calculate the loads using the code or standard to which the building was designed and constructed. If the original design loads are significantly lower than current wind loads, upgrading the load resistance of the building envelope and/or structure should be considered (see Section 6.2.4.2). An alternative to comparing current loads with original design loads is to evaluate the resistance of the existing facility as a function of the current wind loads to determine what elements are highly overstressed.

Step 2: Perform a field investigation to evaluate the primary building envelope elements, rooftop equipment, and structural system elements, to determine if the school was generally constructed as indicated on the original contract drawings. As part of the investigation, the primary elements should be checked for deterioration. Load path continuity should also be checked.

The above evaluations will allow development of a vulnerability assessment that can be used along with the site's wind characteristics to assess the risk. If the results of either step indicate the need for remedial work, see Section 6.4.

6.2.4.3 Portable Classrooms

Unless portable classrooms are designed and constructed (including anchorage to the ground—see Figure 6-27) to meet the same wind loads as the main school building, students and faculty should be considered at risk during high winds. Therefore, portable classrooms should not be occupied when high winds are forecast (even though the forecast speeds are well below design wind conditions for the main building). Also, during winds that are well below design wind conditions, wind-borne debris from disintegrating portable classrooms could impact and damage the main school building and/or nearby residences (Figure 6-28).

Figure 6-27:
Unlike the portable classroom shown in Figure 6-22, with the thick T-shaped plates and taut turnbuckles, this portable classroom has a robust anchorage to the ground. Hurricane Francis (Florida, 2004)

Figure 6-28: Asphalt shingles and vinyl siding blew off of this portable classroom. This type of wind-borne debris can break unprotected glazing. Hurricane Francis (Florida, 2004)

6.3 Requirements and Best Practices in High-Wind Regions

The performance of schools in past wind storms indicates that the most frequent and the most significant factor in the disruption of the operations of these facilities has been the failure of nonstructural building components. While acknowledging the importance of the structural systems, Chapter 6 emphasizes the building envelope components and the nonstructural systems. According to National Institute of Building Sciences (NIBS), the building envelope includes the below-grade basement walls and foundation and floor slab (although these are generally considered part of the building's structural system). The envelope includes everything that separates the interior of a building from the outdoor environment, including the connection of all the nonstructural elements to the building structure. The nonstructural systems include all mechanical, electrical, electronic, communications, and lightning protection systems. Historically, damage to roof coverings and rooftop equipment has been the leading cause of building performance problems during windstorms. Special consideration should be given to the problem of water infiltration through failed building envelope components, which can cause severe disruptions in the functioning of schools.

The key to enhanced wind performance is paying sufficient attention to all phases of the construction process (including site selection, design, and construction) and to post-occupancy maintenance and repair. Of course, the school district must first budget sufficient funds for these efforts (see Sections 6.2.2.2 and 6.2.3.2).

School Design Considerations In Hurricane-Prone Regions

Following the general design and construction recommendations, this manual presents recommendations specific to schools located in hurricane-prone regions. These recommendations are additional to the ones presented for schools located outside of hurricane-prone regions, and in many cases supersede those recommendations. Schools located in hurricane-prone regions require special design and construction attention because of the unique characteristics of this type of windstorm. Hurricanes can bring very high winds that last for many hours, which can lead to material fatigue failures. The variability of wind direction increases the probability that the wind will approach the building at the most critical angle. Hurricanes also generate a large amount of wind-borne debris, which can damage various building components and cause injury and death. In order to ensure continuity of service during and after hurricanes, the design, construction, and maintenance of schools should be very robust to provide sufficient resiliency to withstand the effects of hurricanes.

Designing a portion of a school to be used as a safe room requires the designer to consider additional design criteria beyond what is presented in this chapter. To find the design criteria for a safe room in a school, refer to FEMA 361 and Section 6.5 of this document.

6.3.1 General School Design Considerations

6.3.1.1 Site

When selecting land for a school, sites located in Exposure D (see ASCE 7 for exposure definitions) should be avoided if possible. Selecting a site in Exposure C or preferably in Exposure B decreases the wind loads. Also, where possible, avoid selecting sites located on an escarpment or the upper half of a hill, where the abrupt change in the topography would result in increased wind loads.[12]

Trees with trunks larger than 6 inches in diameter, poles (e.g., light fixture poles, flagpoles, and power poles), or towers (e.g., electrical transmission and large communication towers) should not be placed near the building. Falling trees, poles, and towers can severely damage a school and injure the occupants. Large trees can crash through pre-engineered metal buildings and wood frame construction (see Figure 6-29). Falling trees can also rupture roof membranes and break windows.

12 When selecting a site on an escarpment or the upper half of a hill is necessary, the ASCE 7 design procedure accounts for wind speed-up associated with this abrupt change in topography.

Figure 6-29:
This fallen tree caused minor damage to these portable classrooms. However, had the tree landed on the classroom at the left of the photograph, it could have caused injuries if the building had been occupied. Although portable classrooms are not occupied during hurricanes, they are frequently occupied during thunderstorms, which often topple trees. Estimated wind speed: 105 to 115 mph. Hurricane Ivan (Florida, 2004)

Street signage should be designed to resist the design wind loads so that toppled signs do not block access roads or become wind-blown debris. AASHTO LTS-4-5 provides guidance for determining wind loads on highway signs.

Providing at least two means of site egress is prudent for all schools, but is particularly important for schools in hurricane-prone regions. If one route becomes blocked by trees or other debris, or by floodwaters, the other access route may still be available.

To the extent possible, site portable classrooms so that, if they disintegrate during a storm that approaches from the prevailing wind direction, debris will avoid impacting the main school building and residences. Debris can travel in excess of 300 feet. Destructive winds from hurricanes and tornadoes can approach from any direction. These storms can also throw debris much farther.

6.3.1.2 School Design

Good wind performance depends on good design (including details and specifications), materials, installation, maintenance, and repair. A significant shortcoming in any of these five elements could jeopardize the performance of a school against wind. Design, however, is the key element to achieving good performance of a building against wind damage. Design inadequacies frequently cannot be compensated for with other elements. Good design, however, can compensate for other inadequacies to some extent. The following steps should be included in the design process for schools.

Step 1: Calculate Loads

Calculate loads on the MWFRS, the building envelope, and rooftop equipment in accordance with the latest edition of ASCE 7 or the local building code, whichever procedure results in the highest loads. In calculating wind loads, design professionals should consider the following items.

Risk Category: This manual recommends that all schools be classified as Risk Category III or IV buildings.

Wind directionality factor: The ASCE 7 wind load calculation procedure incorporates a wind directionality factor (K_d). The directionality factor accounts for the reduced probability of maximum winds coming from any given direction. By applying the prescribed value of 0.85, the loads are reduced by 15 percent. Because hurricane winds can come from any direction, and because of the historically poor performance of building envelopes and rooftop equipment, this manual recommends a more conservative approach for schools in hurricane-prone regions. A directionality factor of 1.0 is recommended for the building envelope and rooftop equipment (a load increase over what is required by ASCE 7). For the MWFRS, a directionality factor of 0.85 is recommended (hence, no change for MWFRS).

For assistance in applying the provisions of ASCE 7, refer to the Applied Technology Council's (ATC) Design Guide 2, *Basic Wind Engineering for Low-Rise Buildings*. Topics include how to determine mean roof height for various building shapes, how to determine the building exposure, how to determine a building's enclosure category, and how to apply loads using the three analytical methods given in ASCE 7 in order to help the user understand the differences in and the sensitivities to these methods. This Guide is based on the 2005 edition of ASCE 7. A future edition of the Guide will be based on the 2010 edition of ASCE 7.

In the past, design professionals seldom performed load calculations on the building envelope (i.e., roof and wall coverings, doors, windows, and skylights) and rooftop equipment. These building components are the ones that have failed the most during past wind events. In large part, they failed because of the lack of proper load determination and inappropriate design of these elements. It is imperative that design professionals determine the loads for the building envelope and rooftop equipment, and design them to accommodate such loads.

The design wind loads for a Risk Category III or IV building are 15 percent greater than for Category II building. This load increase is intended to make Category III and IV buildings more capable of resisting the wind pressures induced by stronger, rarer hurricanes than Category II buildings.

Even if a school (or portion thereof) is hardened for improved wind resistance and damage reduction, the facility will not provide hurricane or tornado life-safety protection unless it has been designed and constructed to meet the criteria in FEMA 361 or the ICC 500. See Section 6.5.

Uplift loads on roof assemblies can also be determined from FM Global (FMG) Data Sheets (dates vary). If the school is FMG insured, and the FMG-derived loads are higher than those derived from ASCE 7 or the building code, the FMG loads should govern. However, if the ASCE 7 or code-derived loads are higher than those from FMG, the ASCE 7 or code-derived loads should govern (whichever procedure results in the highest loads).

When using allowable stress design, a safety factor is applied to account for reasonable variations in material strengths, construction workmanship, and conditions when the actual wind speed somewhat exceeds design wind speed. For design purposes, the ultimate resistance an assembly achieves in testing is reduced by the safety factor. For example, if a roof assembly resisted an uplift pressure of 100 pounds per square foot (psf), after applying a safety factor of 2, the assembly would be suitable where the design load after application of the load combination reduction factor was 50 psf or less.[13] Conversely, if the design load after application of the load combination is known, multiplying it by the safety factor equals the minimum required test pressure (e.g., 50 psf design load multiplied by a safety factor of 2 equals a minimum required test pressure of 100 psf).

Step 2: Determine Load Resistance

When using allowable stress design, after loads have been determined, it is necessary to determine a reasonable safety factor in order to select the minimum required load resistance. For building envelope systems, a minimum safety factor of 2 is recommended. For anchoring exterior-mounted mechanical, electrical, and communications equipment (such as satellite dishes), a minimum safety factor of 3 is recommended. When using allowable stress design, refer to the load combinations specified in ASCE 7. When using strength design, load combinations and load factors specified in ASCE 7 are used.

For structural members and cladding elements where strength design can be used, load resistance can be determined by calculations. For other elements where allowable stress design is used (such as most types of roof coverings), load resistance is primarily obtained from system testing.

The load resistance criteria need to be provided in contract documents. For structural elements, the designer of record typically accounts for load resistance by indicating the material, size, spacing, and connection of the elements. For nonstructural elements, such as roof coverings or windows, the load and safety factor can be specified. In this case, the specifications should require the contractor's submittals to demonstrate that the system will meet the load resistance criteria. This performance specification approach is necessary if, at the time of the design, it is unknown who will manufacture the system.

Regardless of which approach is used, it is important that the designer of record ensure that it can be demonstrated, via calculations or tests, that the structure, building envelope, and nonstructural systems (exterior-mounted mechanical, electrical, and communications equipment) have sufficient strength to resist design wind loads.

13 If the 2005 or earlier edition of ASCE 7 is used, the design wind load prior to application of

Step 3: Detailed Design

It is vital to design, detail, and specify the structural system, building envelope, and exterior-mounted mechanical, electrical, and communications equipment to meet the factored design loads (based on appropriate analytical or test methods). It is also vital to respond to the risk assessment criteria discussed in Section 6.2.4, as appropriate.

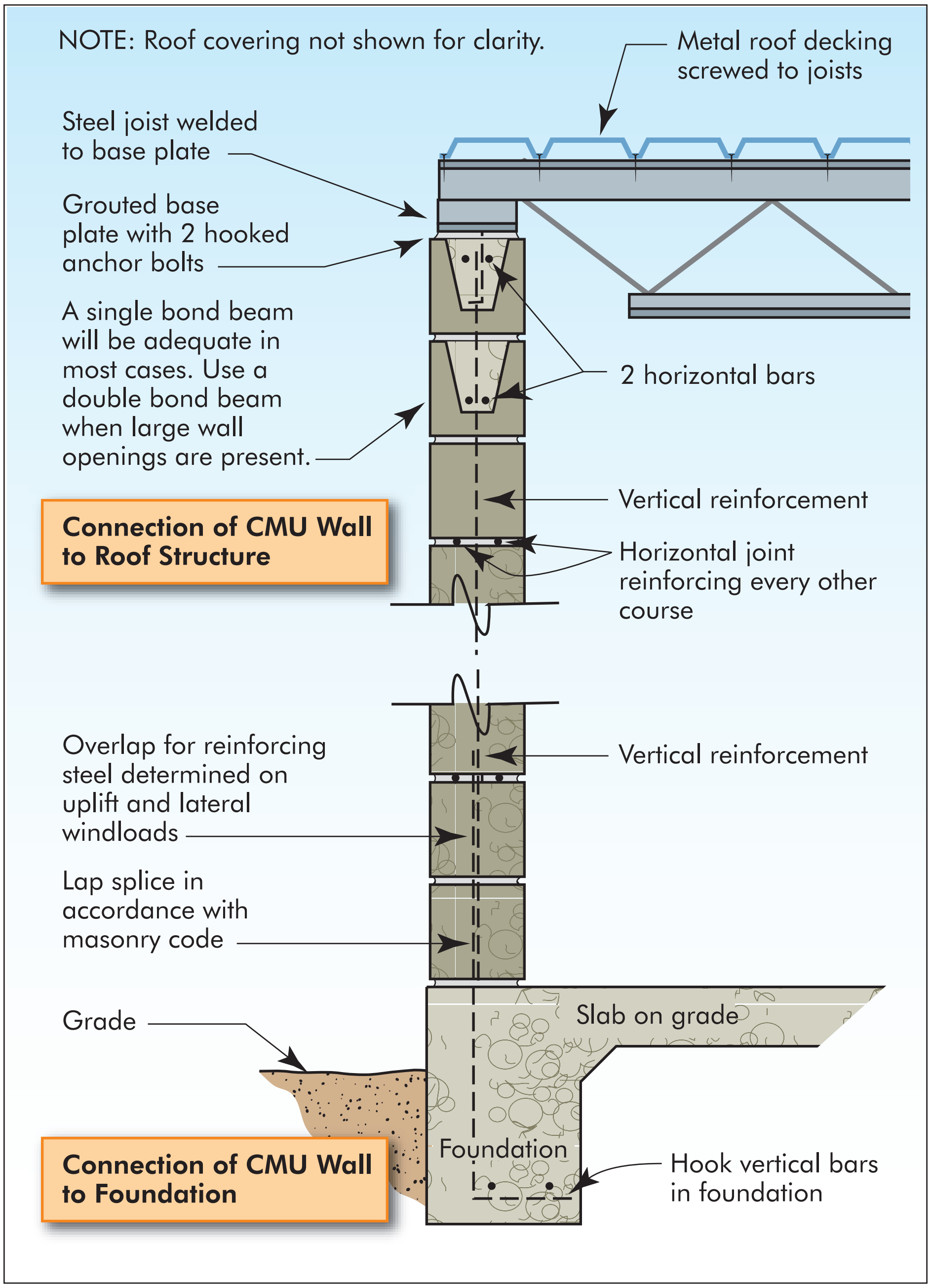
As part of the detailed design effort, load path continuity should be clearly indicated in the contract documents via illustration of connection details. Load paths need to accommodate design uplift, racking, and overturning loads. Load path continuity obviously applies to MWFRS elements, but it also applies to building envelope elements. Figure 6-30 shows load path discontinuities within a roof covering system. In this system, metal roof panels were attached to plywood, which was attached to 4x4 nailers running cross-slope. These top nailers were attached to 4x4 nailers that ran up-slope. The top nailers were inadequately attached to the bottom nailers and the bottom nailers were inadequately attached to the roof structure. To effectively attach the top nailer to the bottom nailer, high-strength connectors such as metal framing connectors are needed. To effectively attach the bottom nailers, a variety of fasteners may be used, provided a sufficient number are used.

Figure 6-30:
In most of the areas on this roof, the connection of the top nailer to the bottom nailer was the weakest link. However, in a few locations, the connection of the bottom nailer to the roof structure was the weak link (three of the blown-off bottom nailers are shown by the red lines).

Connections are a key aspect of load path continuity between various structural and nonstructural building elements. In a window, for example, the glass must be strong enough to resist the wind pressure and must be adequately anchored to the window frame, the frame adequately anchored to the wall, the wall to the foundation, and the foundation to the ground. As loads increase, greater load capacity must be developed in the connections.

Figure 6-31 illustrates the load path concept. Members are sized to accommodate the design loads. Connections are designed to transfer uplift loads applied to the roof, and the positive and negative loads applied to the exterior bearing walls, down to the foundation and into the ground. The roof covering (and wall covering, if there is one) is also part of the load path. To avoid blow-off, the nonstructural elements must also be adequately attached to the structure.

Figure 6-31: Illustration of load path continuity



As part of the detailed design process, special consideration should be given to the durability of materials and water infiltration.

Durability: Because some locales have very aggressive atmospheric corrosion (such as areas near oceans), special attention needs to be given to the specification of adequate protection for ferrous metals, or to specify alternative metals such as stainless steel. FEMA TB-8, *Corrosion Protection for Metal Connectors in Coastal Areas* (1996), contains information on corrosion protection. Attention also needs to be given to dry rot avoidance, for example, by specifying preservative-treated wood or developing details that avoid excessive moisture accumulation. Appendix J of FEMA 55, *Coastal Construction Manual* (2000), presents information on wood durability. Note: An updated version of FEMA 55 is expected to be released in 2011.

Durable materials are particularly important for components that are inaccessible and cannot be inspected regularly (such as fasteners used to attach roof insulation). Special attention also needs to be given to details. For example, details that do not allow water to stand at connections or sills are preferred. Without special attention to material selection and details, the demands on maintenance and repair will be increased, along with the likelihood of failure of components during high winds.

Water infiltration (rain): Although prevention of building collapse and major building damage is the primary goal of wind-resistant design, consideration should also be given to minimizing water damage and subsequent development of mold from the penetration of wind-driven rain. To the extent possible, non-load-bearing walls and door and window frames should be designed in accordance with rain-screen principles. With this approach, it is assumed that some water will penetrate past the face of the building envelope. The water is intercepted in an air-pressure equalized cavity that provides drainage from the cavity to the outer surface of the building. See Sections 6.3.3.1 and 6.3.3.4, and Figure 6-52 for further discussion and an example.

In conjunction with the rain-screen principle, it is desirable to avoid using sealant as the first or only line of defense against water infiltration. When sealant joints are exposed, obtaining long-lasting watertight performance is difficult because of the complexities of sealant joint design and installation (see Figure 6-52, which shows the sealant protected by a removable stop).

Further information on the rain-screen principle can be found in the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

Step 4: Peer Review

If the design team's wind expertise and experience is limited, wind design input and/or peer review should be sought from a qualified individual. The design input or peer review could be arranged for the entire building, or for specific components such as the roof or glazing systems, that are critical and beyond the design team's expertise.

When a room or portion of a school has been design per FEMA 361 to function as a safe room with an occupancy of 50 persons or more, a peer review must be performed for the safe room.

Regardless of the design team's expertise and experience, peer review should be considered when a school:

- is located in an area where the basic wind speed is greater than 120 mph (peak gust)[14]
- will be used for emergency response after a storm
- will be used for a hurricane shelter
- will incorporate a hurricane or tornado safe room or shelter

6.3.1.3 Construction Contract Administration

After a suitable design is complete, the design team should endeavor to ensure that the design intent is achieved during construction. The key elements of construction contract administration are submittal reviews and field observations, as discussed below.

Submittal reviews: The specifications need to stipulate the submittal requirements. This includes specifying what systems require submittals (e.g., windows) and test data (where appropriate). Each submittal should demonstrate the development of a load path through the system and into its supporting element. For example, a window submittal should show that the glazing has sufficient strength, its attachment to the frame is adequate, and the attachment of the frame to the wall is adequate.

During submittal review, it is important for the designer of record to be diligent in ensuring that all required documents are submitted and that they include the necessary information. The submittal information needs to be thoroughly checked to ensure its validity. For example, if an approved method used to demonstrate compliance with the design load has been altered or incorrectly applied, the test data should be rejected, unless the contractor can demonstrate the test method was suitable. Similarly, if a new test method has been developed by a manufacturer or the contractor, the contractor should demonstrate its suitability.

14 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

Field observations: It is recommended that the design team analyze the design to determine which elements are critical to ensuring high-wind performance. The analysis should include the structural system and exterior-mounted electrical equipment, but it should focus on the building envelope and exterior-mounted mechanical and communications equipment. After determining the list of critical elements to be observed, observation frequency and the need for special inspections by an inspection firm should be determined. Observation frequency and the need for special inspections will depend on the magnitude of the results of the risk assessment described in Section 6.2.4, the complexity of the facility, and the competency of the general contractor, subcontractors, and suppliers.

6.3.1.4 Post-Occupancy Inspections, Periodic Maintenance, Repair, and Replacement

The design team should advise the school administration of the importance of periodic inspections, maintenance, and timely repair. It is important for the administration to understand that a facility's wind resistance will degrade over time due to exposure to weather unless it is regularly maintained and repaired. The goal should be to repair or replace items before they fail in a storm. This approach is less expensive than waiting for failure and then repairing the failed components and consequential damage.

> Prior to hurricane landfall, a special roof inspection is recommended. Remove debris and other items that are not anchored so that they do not become wind-borne debris. Also, clean roof drains and sumps so that their drainage capacity is not impaired (see Figure 6-32). Lack of debris maintenance can lead to clogging. If overflow drains or scuppers are also clogged, roof collapse may occur.

The building envelope and exterior-mounted equipment should be inspected once a year by persons knowledgeable of the systems/materials they are inspecting. Items that require maintenance, repair, or replacement should be documented and scheduled for work. For example, the deterioration of glazing is often overlooked. After several years of exposure, scratches and chips can become extensive enough to weaken the glazing. Also, if an engineered film was surface-applied to glazing for wind-borne debris protection, the film should be periodically inspected and replaced before it is no longer effective.

A special inspection is recommended following unusually high winds (such as a thunderstorm with wind speeds of 70 mph peak gust or greater). The purpose of the inspection is to assess whether the storm caused damage that needs to be repaired to maintain building strength and integrity. In addition to inspecting for obvious signs of damage, the inspector should determine if cracks or other openings have developed that may allow water infiltration, which could lead to corrosion or dry rot of concealed components.

Figure 6-32: Dirt and vegetation surrounded this roof drain (red arrow) and impeded drainage. Roof drains should be checked at least annually and cleaned of debris if found. Drains should also be checked prior to hurricane landfall. Hurricane Ike (Texas, 2008)

6.3.1.5 Site and General Design Considerations in Hurricane-Prone Regions

Via ASCE 7, the 2009 edition of the IBC has only two special wind-related provisions pertaining to schools in hurricane-prone regions. One pertains to glazing protection within wind-borne debris regions (as defined in ASCE 7). The other provision pertains to schools that will be used as hurricane evacuation shelters. If used as shelters, schools must be designed as Risk Category IV buildings. These are the only hurricane-related school requirements currently in the IBC. These two additional requirements do not provide adequate protection of occupants of a school during a hurricane, nor do they ensure a school will be functional after a hurricane. Further, a school may comply with IBC, but still remain vulnerable to water and missile penetration through the roof or walls. To mitigate this water and missile vulnerability, see Sections 6.3.2.2, 6.3.3.3, 6.3.3.5, and 6.3.3.7.

During the design phase, the architect should determine from the school district whether or not the school will be designated or used as a hurricane evacuation shelter. If it will be used as a shelter, see Section 6.5 for design recommendations.

The following recommendations are made regarding siting:

- Locate poles, towers, and trees with trunks larger than 6 inches in diameter away from primary site access roads so that they do not block access to, or hit, the facility if toppled.
- Determine if existing buildings within 1,500 feet of the new facility have aggregate surfaced roofs. If roofs with aggregate surfacing are present, it is recommended that the aggregate be removed to prevent it from impacting the new facility. Aggregate removal may necessitate reroofing or other remedial work in order to maintain the roof's fire or wind resistance.
- In cases where a building on a school campus will be used as a hurricane safe room or shelter, if there are multiple buildings on campus, it is recommended that enclosed walkways be designed to connect the buildings. The enclosed walkways (above- or below-grade) are particularly important for protecting people moving between buildings during a hurricane if it becomes necessary to evacuate occupants from one building to another (see Figure 6-33).

Publication 4496 by the American Red Cross (ARC, 2002), *Standards for Hurricane Evacuation Shelter Selection*, provides information regarding assessing existing buildings for use as hurricane shelters. Unless a school has been specifically designed for use as a safe room or shelter, it should only be used as a last resort and only if the school meets the criteria given in ARC 4496.

Figure 6:33:
Open walkways do not provide protection from wind-borne debris. Hurricane Katrina (Mississippi, 2005).

6.3.2 Structural Systems

6.3.2.1 Design Parameters for Structural Systems

Based on post-storm damage evaluations, with the exception of canopies and strong and violent tornado events, the structural systems (i.e., MWFRS and structural components such as roof decking) of schools have typically performed quite well during design wind events. There have, however, been notable exceptions; in these cases, the most common problem has been blow-off of the roof deck, but instances of collapse have also been documented (Figures 6-18, 6-21, 6-24, 6-26, and 6-34). The structural problems have primarily been caused by lack of an adequate load path, with connection failure being a common occurrence. Problems have also been caused by reduced structural capacity due to termites, workmanship errors (commonly associated with steel decks attached by puddle welds), and limited uplift resistance of deck connections in roof perimeters and corners (due to lack of code-required enhancement in older editions of the model codes).

Figure 6-34: The structure on this school was composed of light gauge metal framing, with a proprietary composite deck system composed of light gauge corrugated metal deck and gypsum board. In addition to the gable end wall failure, the asphalt shingles and underlayment were blown off at the corner of the eave and ridge. Estimated wind speed: 140 to 160 mph. Hurricane Charley (Florida, 2004)

With the exception of strong and violent tornado events, structural systems designed and constructed in accordance with the IBC should typically offer adequate wind resistance, provided attention was given to load path continuity and to the durability of building materials (with respect to corrosion and termites). However, the greatest reliability is offered by cast-in-place concrete. There are no known reports of any cast-in-place concrete buildings experiencing a significant structural problem during wind events, including the strongest hurricanes (Category 5) and tornadoes (EF5).

The following design parameters are recommended for structural systems:

- If a pre-engineered metal building is being contemplated, special steps should be taken to ensure the structure has more redundancy than is typically the case with pre-engineered buildings.[15] Steps should be taken to ensure the structure is not vulnerable to progressive collapse in the event a primary bent (steel moment frame) is compromised or bracing components fail.
- Exterior load-bearing walls of masonry or precast concrete should be designed to have sufficient strength to resist external and internal loading when analyzed as C&C. CMU walls should have vertical and horizontal reinforcing and grout to resist wind loads.

15 The structural system of pre-engineered metal buildings is composed of rigid steel frames, secondary members (including roof purlins and wall girts made of Z- or C-shaped members), and bracing.

The connections of precast concrete wall panels should be designed to have sufficient strength to resist wind loads.

- For roof decks, concrete, steel, plywood, or oriented strand board (OSB) is recommended.
- For steel roof decks, it is recommended that a screw attachment be specified, rather than puddle welds or powder-driven pins. Screws are more reliable and much less susceptible to workmanship problems, as illustrated by Figure 6-35. These roof joists and decking blew off and landed several feet from the building. The decking was attached with closely-spaced screws. Because of the strength and reliability of the screwed connections, the decking remained attached to the joists.

Figure 6-35: Even though the roof structure blew off, because of the strength and reliability of the screwed deck connections, the decking remained attached to the joists. Hurricane Charley (Florida, 2004)

Figure 6-36 shows decking that was attached with puddle welds. At most of the welds, there was only superficial bonding of the metal deck to the joist. Only a small portion of the deck near the center of the weld area (as delineated by the circle) was well fused to the joist. Figures 6-37 and 6-38 show problems with acoustical decking attached with powder-driven pins. The pin shown on the left of Figure 6-38 is properly seated. However, the pin at the right did not penetrate far enough into the steel joist below.

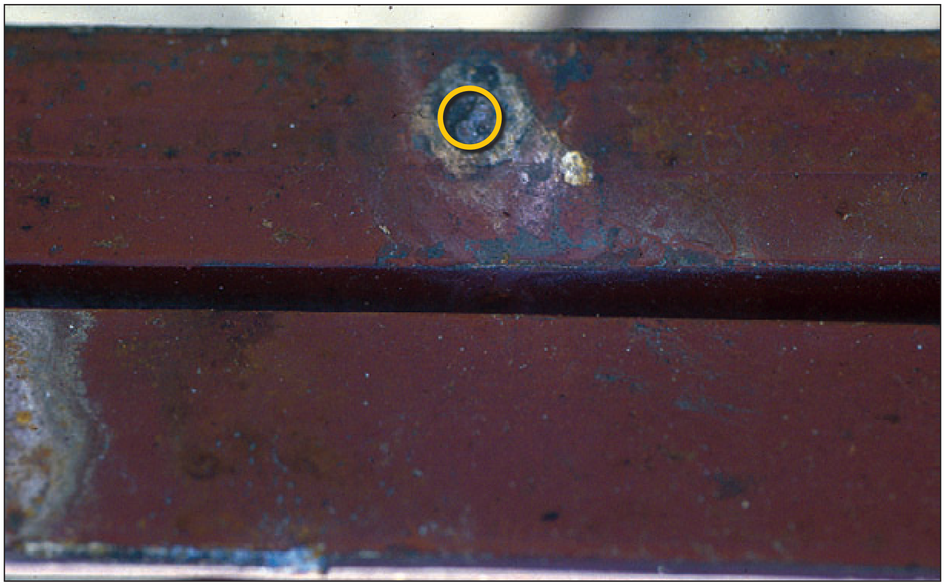


Figure 6-36:
View looking down at the top of a steel joist after the metal decking blew away. Only a small portion of the deck was well fused to the joist (circled area). Tornado (Oklahoma, 1999)

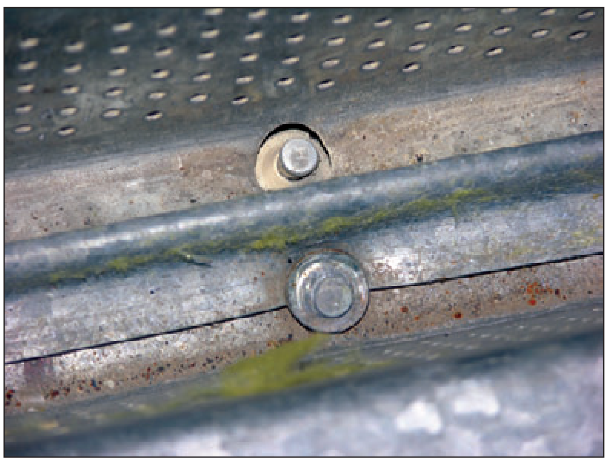


Figure 6-37:
Looking down at a sidelap of a deck attached with powder-driven pins. The washer at the top pin blew through the deck.

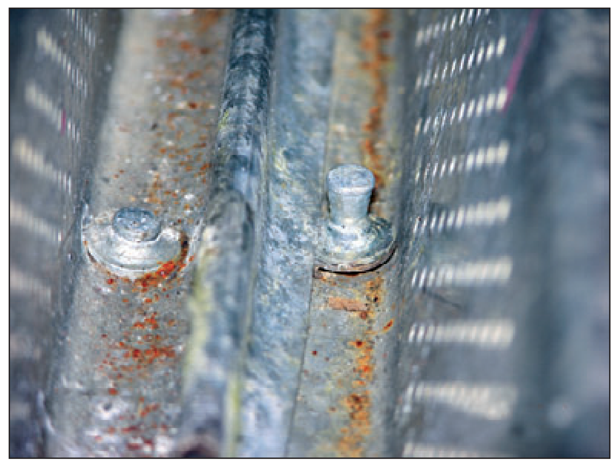


Figure 6-38:
View looking along a sidelap of a deck attached with powder-driven pins. The right pin does not provide adequate uplift and shear resistance.

- For attaching wood-sheathed roof decks, screws, ring-shank, or screw-shank nails are recommended in the corner regions of the roof. Where the basic wind speed is greater than 120 mph, these types of fasteners are also recommended for the perimeter regions of the roof.[16]

16 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

- For precast concrete decks it is recommended that the deck connections be designed to resist the design uplift loads because the deck dead load itself is often insufficient to resist the uplift. The deck in Figure 6-39 had bolts to provide uplift resistance; however, anchor plates and nuts had not been installed. Without the anchor plates, the dead load of the deck was insufficient to resist the wind uplift load.
- For precast Tee decks, it is recommended that the reinforcing be designed to accommodate the uplift loads in addition to the gravity loads. Otherwise, large uplift forces can cause member failure due to the Tee's own pre-stress forces after the uplift load exceeds the dead load of the Tee. This type of failure occurred at one of the roof panels shown in Figure 6-40, where a panel lifted because of the combined effects of wind uplift and pre-tension. Also, because the connections between the roof and wall panels provided very little uplift load resistance, several other roof and wall panels collapsed.
- For buildings that have mechanically attached single-ply or modified bitumen membranes, designers should refer to the decking recommendations presented in the *Wind Design Guide for Mechanically Attached Flexible Membrane Roofs,* B1049 (National Research Council of Canada, 2005).

If an FMG-rated roof assembly is specified, the roof deck also needs to comply with the FMG criteria. See text box about FM Global in Section 6.3.3.6.

Figure 6-39: Portions of this waffled precast concrete roof deck were blown off. Typhoon Paka (Guam, 1997)

Figure 6-40:
Twin-Tee roof panel lifted as a result of the combined effects of wind uplift and pre-tension. Tornado (Missouri, May 2003)

Walkway and entrance canopies are often damaged during high winds (see Figure 6-41). Wind-borne debris from damaged canopies can damage nearby buildings and injure people; hence, these elements should also receive design and construction attention.

Figure 6-41:
The wind speed was sufficient to collapse this school's canopy, but the speed was not high enough to blow the canopy debris very far. Hurricane Francis (Florida, 2004)

ASCE 7-05 provides pressure coefficients for open canopies of various slopes (referred to as "free roofs" in ASCE 7). The free roof figures for MWFRS in ASCE 7-05 (Figures 6-18A to 6-18D) include two load cases, Case A and Case B. While there is no discussion describing the two load cases, they pertain to fluctuating loads and are intended to represent upper and lower limits of instantaneous wind pressures. Loads for both cases must be calculated to determine the critical loads. Figures 6-18A to 6-18C are for a wind direction normal to the ridge. For wind direction parallel to the ridge, use Figure 6-18D in ASCE 7-05.

In ASCE 7-10, Commentary Section C27.4.3 was revised to include discussion of the two load cases. The Commentary was also expanded to include discussion about "clear wind flow" and "obstructed wind flow," which pertains to storage of goods or materials under the free roof (which restrict wind flow).

6.3.2.2 Design Parameters for Structural Systems in Hurricane-Prone Regions

Because of the exceptionally good wind performance and wind-borne debris resistance that reinforced cast-in-place concrete structures offer, a reinforced concrete roof deck and reinforced concrete or reinforced and fully grouted CMU exterior walls are recommended as follows:

Roof deck: A minimum 4-inch thick cast-in-place reinforced concrete deck is the preferred deck. Other recommended decks are minimum 4-inch thick structural concrete topping over steel decking, and precast concrete with an additional minimum 4-inch structural concrete topping. With these deck types, deck blow-off or penetration by wind-borne debris is highly unlikely, thus avoiding water infiltration (when combined with the roof system recommendations given in Section 6.3.3.7). Figure 6-42 illustrates the type of damage that can occur to other types of decks impacted by large momentum debris.

If precast concrete is used for the roof or wall structure, the connections should be carefully designed, detailed, and constructed.

Exterior load-bearing walls: A minimum 6-inch thick, cast-in-place concrete wall reinforced with #4 rebars at 12 inches on center each way is the preferred wall. Other recommended walls are a minimum 8-inch thick, fully grouted CMU reinforced vertically with #4 rebars at 16 inches on center, and precast concrete that is a minimum 6-inches thick and reinforced equivalent to the recommendations for cast-in-place walls.

Figure 6-42:
At the school shown in Figure 6-34, wind-borne debris ruptured the proprietary composite deck system composed of light gauge corrugated metal deck and gypsum board. Estimated wind speed: 140 to 160 mph. Hurricane Charley (Florida, 2004)

6.3.3 Building Envelope

The following section highlights the design considerations for building envelope components that have historically sustained the greatest and most frequent damage in high winds.

The design considerations for building envelope components of schools in hurricane-prone regions include a number of additional recommendations. The principal concern that should be addressed is the additional risk from wind-borne debris and water leakage. Design considerations specific to hurricane-prone regions are discussed in Sections 6.3.3.3, 6.3.3.5, and 6.3.3.7. Design guidance for building envelope components of safe rooms within schools is addressed in Section 6.5.

6.3.3.1 Exterior Doors

This section addresses primary and secondary egress doors, sectional (garage) doors, and rolling doors. Although blow-off of personnel doors is uncommon, it can cause serious problems. Blown-off doors allow entrance of rain and tumbling doors can damage buildings and cause injuries.

For further general information on doors, see "Fenestration Systems" in the National Institute of Building Sciences' Building Envelope Design Guide (www.wbdg.org/design/envelope.php).

Although many schools do not have sectional or rolling doors, blow-off of these types of doors is quite common. These failures are typically caused by the use of door and track assemblies that have insufficient wind resistance, or by inadequate attachment of the tracks or nailers to the wall.

Loads and Resistance

The IBC requires that the door assembly (i.e., door, hardware, frame, and frame attachment to the wall) be of sufficient strength to resist the positive and negative design wind pressure. Design professionals should require that doors comply with wind load testing in accordance with ASTM E 1233. Design professionals should also specify the attachment of the door frame to the wall (e.g., type, size, spacing, and edge distance of frame fasteners). For sectional and rolling doors attached to wood nailers, design professionals should also specify the attachment of the nailer to the wall.

For design guidance on attachment of door frames, see Technical Data Sheet #161, *Connecting Garage Door Jambs to Building Framing*, published by the Door & Access Systems Manufacturers Association, 2003 (revised May 2008). Available at www.dasma.com.

Water Infiltration

Heavy rain that accompanies high winds (e.g., thunderstorms, tropical storms, and hurricanes) can cause significant wind-driven water infiltration problems. The magnitude of the problem increases with the wind speed. Leakage can occur between the door and its frame, the frame and the wall, and between the threshold and the door. When wind speeds approach 165 mph, some leakage should be anticipated because of the very high wind pressures and numerous opportunities for leakage path development.[17]

The following recommendations should be considered to minimize infiltration around exterior doors.

Vestibule: Adding a vestibule allows both the inner and outer doors to be equipped with weatherstripping. The vestibule can be designed with water-resistant finishes (e.g., concrete or tile) and the floor can be equipped with a drain. In addition, installing exterior threshold trench drains can be helpful (openings must be small enough to avoid trapping high-heeled shoes). Note that trench drains do not eliminate the problem, since water can still penetrate at door edges.

Where corrosion is problematic, anodized aluminum or galvanized doors and frames, and stainless steel frame anchors and hardware are recommended.

17 The 165-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 120 mph.

Door swing: Out-swinging doors have weatherstripping on the interior side of the door, where it is less susceptible to degradation, which is an advantage when compared to in-swinging doors. Some interlocking weatherstripping assemblies are available for out-swinging doors.

For primary swinging entry/exit doors, exit door hardware is recommended to minimize the possibility of the doors being pulled open by wind suction. Exit hardware with top and bottom rods is more secure than exit hardware that latches at the jamb.

The successful integration of the door frame and the wall is a special challenge when designing doors. See Section 6.3.3.2 for discussion of this juncture.

ASTM E 2112 provides information pertaining to the installation of doors, including the use of sill pan flashings with end dams and rear legs (see Figure 6-43). It is recommended that designers use ASTM E 2112 as a design resource.

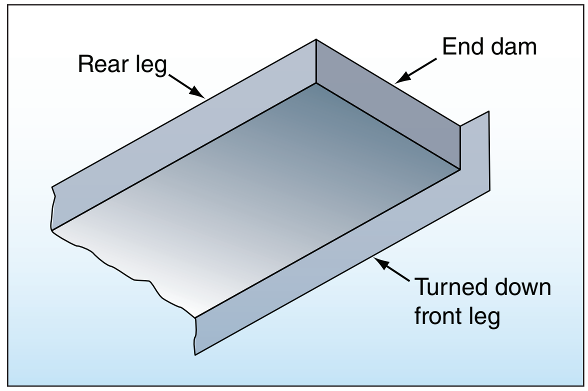


Figure 6-43:
Door sill pan flashing with end dams, rear leg, and turned-down front leg

Weatherstripping

A variety of pre-manufactured weatherstripping components is available, including drips, door shoes and bottoms, thresholds, and jamb/head weatherstripping.

Drips: These are intended to shed water away from the opening between the frame and the door head, and the opening between the door bottom and the threshold (see Figures 6-44 and 6-45). Alternatively, a door sweep can be specified (see Figure 6-45). For high-traffic doors, periodic replacement of the neoprene components will be necessary.

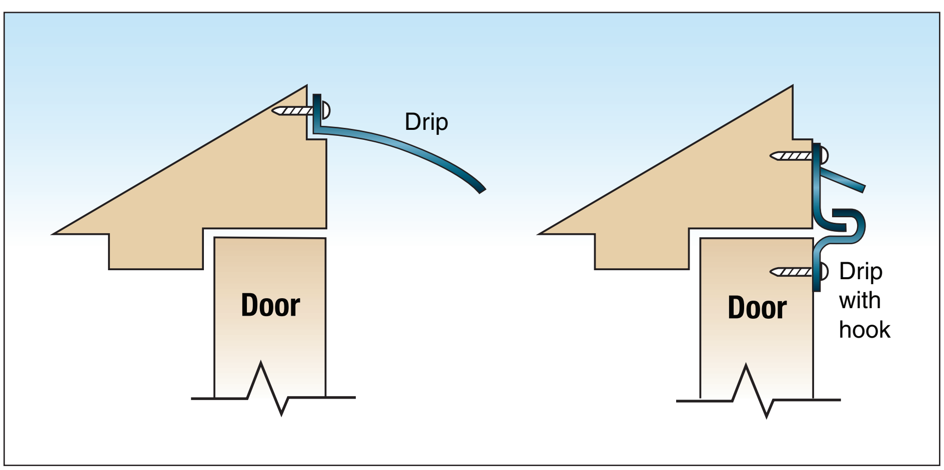


Figure 6-44:
Drip at door head and drip with hook at head

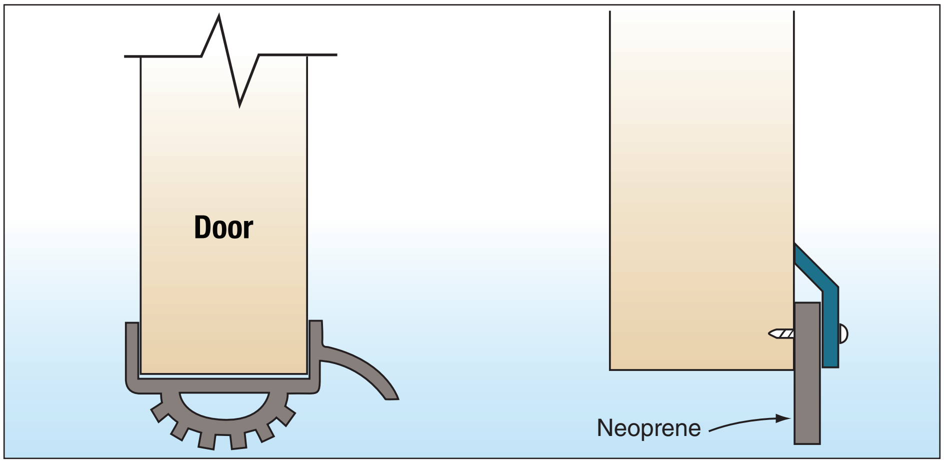


Figure 6-45: Door shoe with drip and vinyl seal (left); neoprene door sweep (right)

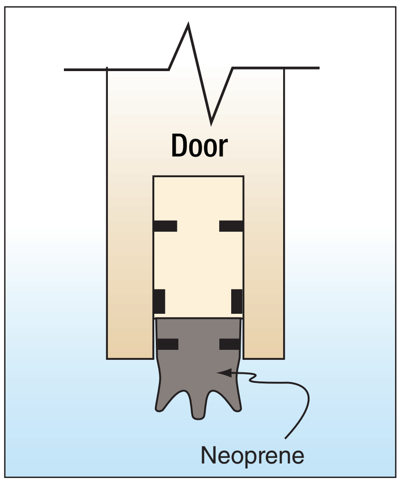


Figure 6-46: Automatic door bottom

Door shoes and bottoms: These are intended to minimize the gap between the door and the threshold. Figure 6-45 illustrates a door shoe that incorporates a drip. Figure 6-46 illustrates an automatic door bottom. Door bottoms can be surface-mounted or mortised. For high-traffic doors, periodic replacement of the vinyl or neoprene components will be necessary.

Thresholds: These are available to suit a variety of conditions. Thresholds with high (e.g., 1-inch) vertical offsets offer enhanced resistance to wind-driven water infiltration. However, the offset is limited where the thresholds are required to comply with the Americans with Disabilities Act (ADA), or at high-traffic doors. At other doors, high offsets are preferred.

Thresholds can be interlocked with the door (see Figure 6-47), or thresholds can have a stop and seal (see Figure 6-48). In some instances, the threshold is set directly on the floor. Where this is appropriate, setting the threshold in butyl sealant is recommended to avoid water infiltration between the threshold and the floor. In other instances, the threshold is set on a pan flashing (as previously discussed in this section). If the threshold has weep holes, specify that the weep holes not be obstructed during construction (see Figure 6-47).

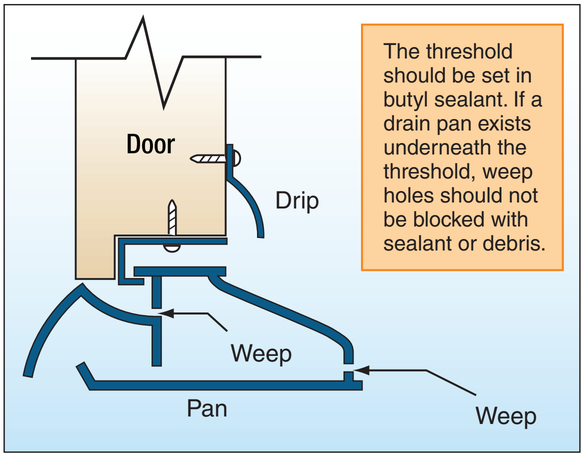


Figure 6-47:
Interlocking threshold with drain pan

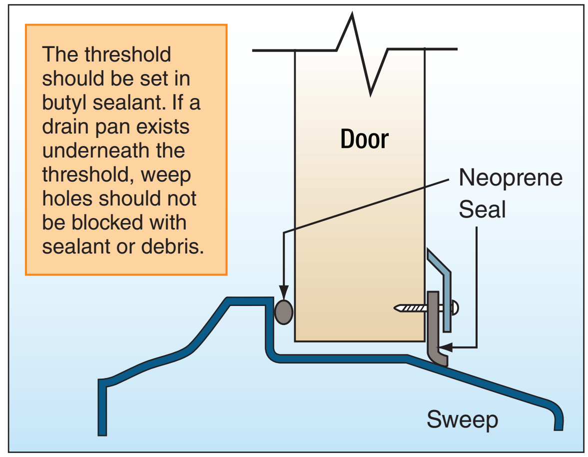


Figure 6-48:
Threshold with stop and seal

Adjustable jamb/head weatherstripping: This type of weatherstripping is recommended because the wide sponge neoprene offers good contact with the door (see Figure 6-49). The adjustment feature also helps to ensure good contact, provided the proper adjustment is maintained.

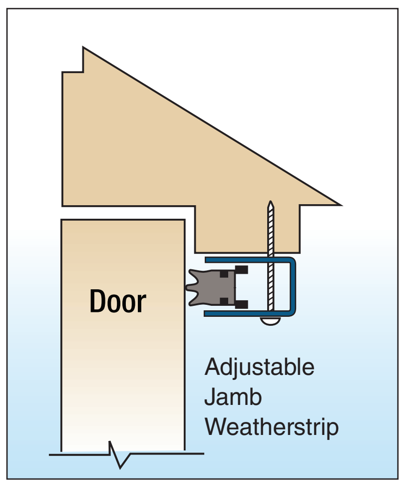


Figure 6-49:
Adjustable jamb/head weatherstripping

Meeting stile: At the meeting stile of pairs of doors, an overlapping astragal weatherstripping offers greater protection than weatherstripping that does not overlap.

6.3.3.2 Windows and Skylights

This section addresses general design considerations for exterior windows and skylights. For additional information on windows and skylights located in hurricane-prone regions, see Section 6.3.3.3.

Loads and Resistance

The IBC requires that windows, curtain walls, and skylight assemblies (i.e., the glazing, frame, and frame attachment to the wall or roof) have sufficient strength to resist the positive and negative design wind pressure (see Figure 6-50). Design professionals should specify that these assemblies

> For further general information on windows, see the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

comply with wind load testing in accordance with ASTM E 1233. It is important to specify an adequate load path and to check its continuity during submittal review.

Where water infiltration protection is particularly demanding and important, it is recommended that on-site water infiltration testing in accordance with ASTM E 1105, be specified.

Figure 6-50: Two complete windows, including frames, blew out as a result of an inadequate number of fasteners. Typhoon Paka (Guam, 1997)

Water Infiltration

Heavy rain accompanied by high winds can cause wind-driven water infiltration problems. The magnitude of the problem increases with the wind speed. Leakage can occur at the glazing/frame interface, the frame itself, or between the frame and wall. When the basic wind speed is greater than 165 mph, because of the very high design wind pressures and numerous opportunities for leakage path development, some leakage should be anticipated when the design wind speed conditions are approached.[18]

Where corrosion is problematic, anodized aluminum or galvanized window frames, and stainless steel frame anchors and hardware are recommended.

The successful integration of windows and curtain walls into exterior walls is a challenge in protecting against water infiltration. To the extent possible, when detailing the interface between the wall and the window or curtain wall units, designers should rely on sealants as the secondary line of defense against water infiltration, rather than making the sealant the primary protection. If a sealant

18 The 165-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 120 mph.

joint is the first line of defense, a second line of defense should be designed to intercept and drain water that drives past the sealant joint.

When designing joints between walls and windows and curtain wall units, consider the shape of the sealant joint (i.e., a square joint is typically preferred) and the type of sealant to be specified. The sealant joint should be designed to enable the sealant to bond on only two opposing surfaces (i.e., a backer rod or bond-breaker tape should be specified). Butyl is recommended as a sealant for concealed joints, and polyurethane for exposed joints. During installation, cleanliness of the sealant substrate is important (particularly if polyurethane or silicone sealants are specified), as is the tooling of the sealant. ASTM E 2112 provides guidance on the design of sealant joints, as well as other information pertaining to the installation of windows, including the use of sill pan flashings with end dams and rear legs (see Figure 6-51). Windows that do not have nailing flanges should typically be installed over a pan flashing. It is recommended that designers use ASTM E 2112 as a design resource.

The maximum test pressure used in the current ASTM test standard for evaluating resistance of window units to wind-driven rain is well below design wind pressures. Therefore, units that demonstrate adequate wind-driven rain resistance during testing may experience leakage during actual wind events.

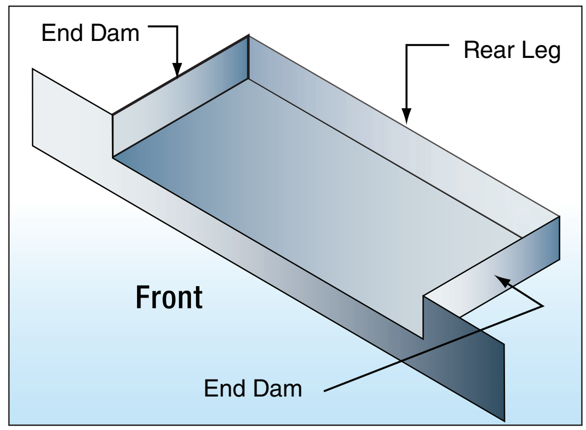


Figure 6-51: View of a typical window sill pan flashing with end dams, rear leg, and turned-down front leg.

SOURCE: ASTM E 2112

Sealant joints can be protected with a removable stop, as illustrated in Figure 6-52. The stop protects the sealant from direct exposure to the weather and reduces the possibility of wind-driven rain penetration.

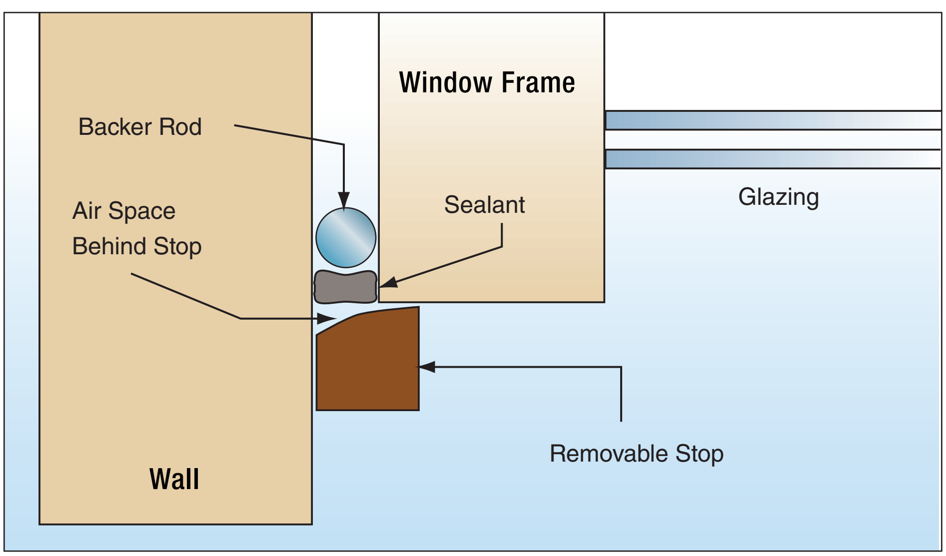


Figure 6-52: Protecting sealant retards weathering and reduces the exposure to wind-driven rain

6.3.3.3 Windows and Skylights in Hurricane-Prone Regions

Exterior glazing that is not impact-resistant (such as laminated glass or polycarbonate) or protected by shutters is extremely susceptible to breaking if struck by wind-borne debris. Even small, low-momentum missiles can easily break glazing that is not protected. At the building shown in Figure 6-53, approximately 400 windows were broken. Most of the breakage was caused by wind-blown aggregate from the building's aggregate-ballasted single-ply membrane roofs, and aggregate from built-up roofs. With broken windows, a substantial amount of water can be blown into a building, and the internal air pressure can be greatly increased, which may damage the interior partitions and ceilings.

Figure 6-53: Plywood panels (black continuous bands) installed after the glass spandrel panels were broken by roof aggregate.[19] Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

In order to minimize interior damage, the IBC, through ASCE 7, prescribes that exterior glazing in wind-borne debris regions be impact-resistant, or be protected with an impact-resistant covering (shutters). ASCE 7 refers to ASTM E 1996 for missile loads and to ASTM E 1886 for the test method to be used to demonstrate compliance with the E 1996 load criteria. In addition to testing impact resistance, the window unit is subjected to pressure cycling after test missile impact to evaluate whether the window can still resist wind loads. If wind-borne debris glazing protection is provided by shutters,

Protection of glazing for safe rooms must meet debris impact criteria that is more restrictive (significant) than that presented in the building codes and the ICC 500. See Chapter 3 of FEMA 361 for the design criteria for debris impact resistance for safe rooms.

19 Glass spandrel panels are opaque glass. They are placed in curtain walls to conceal the area between the ceiling and the floor above.

the glazing is still required by ASCE 7 to meet the positive and negative design air pressures.

Window assemblies with laminated glass that have passed ASTM E 1886 can also be easily broken by low-momentum debris. However, unlike other types of glass, when laminated glass breaks, it is expected to remain in the frame and prevent entrance of wind and water. Cost will be incurred to replace the broken laminated glass, but that cost is significantly less than the cost of repairing interior wind and water damage, and the costs associated with loss of use of the school during repair work. Figure 6-54 shows laminated glass that was broken, but protected the building's interior as intended.

For Category III and IV buildings in areas with a basic wind speed of 130 mph or greater, the glazing or shutter is required to resist a larger momentum test missile than would Category II, III, and IV buildings in areas with basic wind speeds less than 130 mph. (Note: The 2009 edition of ASTM E 1996 references 130 mph based on ASCE 7-05. When using ASCE 7-10, a basic wind speed of 175 mph applies for Risk Category III and IV buildings).

Although the ASCE 7 wind-borne debris provisions only apply to glazing within a portion of hurricane-prone regions, it is recommended that all schools located where the basic wind speed is 135 mph or greater comply with the following recommendation:[20]

- To avoid interior wind and water damage, it is recommended that exterior glazing be designed to resist the test Missile D load (unless the E test missile is required as previously discussed) specified in ASTM E 1996 (see text box on the following page).

Figure 6-54:
The red arrow shows a piece of laminated glass that was broken, but remained in the frame to protect the building's interior. The blue arrow shows unbroken laminated glass. The yellow arrows show granite wall panels. Estimated wind speed: 105 mph. Hurricane Katrina (Louisiana, 2005)

20 The 135-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 100 mph.

ASTM E 1996 specifies five missile categories, A through E. The missiles are of various weights and fired at various velocities during testing. Building type (critical or non-critical) and basic wind speed determine the missiles required for testing. Of the five missiles, the E missile has the greatest momentum. Missile E is required for critical facilities located where the basic wind speed is greater than or equal to 130 mph. Missile D is permitted where the basic wind speed is less than 130 mph. FEMA 361 also specifies a missile for shelters. The shelter missile has much greater momentum than the D and E missiles, as shown below:

Missile	Missile Weight	Impact Speed	Momentum
ASTM E 1996—D	9 pound 2x4 lumber	50 feet per second (34 mph)	14 lb_f -s*
ASTM E 1996—E	9 pound 2x4 lumber	80 feet per second (55 mph)	22 lb_f -s*
FEMA 361 (Shelter Missile)	15 pound 2x4 lumber	147 feet per second (100 mph)	68 lb_f -s*

*lb_f -s = POUNDS FORCE PER SECOND

- For those facilities where glazing resistant to bomb blasts is desired, the windows and glazed doors can be designed to accommodate wind pressure, missile loads, and blast pressure. However, the window and door units need to be tested for missile loads and cyclic air pressure, as well as for blast. A unit that meets blast criteria will not necessarily meet the ASTM E 1996 and ASTM E 1886 criteria, and vice versa.

For further information on designing glazing to resist blast, see the “Blast Safety” resource pages of the National Institute of Building Sciences’ *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

With the advent of building codes requiring glazing protection in wind-borne debris regions, a variety of shutter designs have entered the market. Shutters typically have a lower initial cost than laminated glass. However, unless the shutter is permanently anchored to the building (e.g., an accordion shutter), storage space will be needed. Also, when a hurricane is forecast, costs will be incurred each time shutters are installed and removed. The cost and difficulty of shutter deployment and demobilization on upper-level glazing may be avoided by using motorized shutters, although laminated glass may be a more economical solution. For further information on shutters, see Section 6.4.2.1.

For further general information on non-load-bearing walls and wall coverings, see the National Institute of Building Sciences’ *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

6.3.3.4 Non-Load-Bearing Walls, Wall Coverings, and Soffits

This section addresses exterior non-load-bearing walls, exterior wall coverings, and soffits, as well as the underside of elevated floors, and provides guidance for interior non-load-bearing masonry walls. See Section 6.4.3.5 for additional information pertaining to non-load-bearing walls, exterior wall coverings, and soffits for schools located in hurricane-prone regions.

> Where corrosion is a problem, stainless steel fasteners are recommended for wall and soffit systems. For other components (e.g., furring, blocking, struts, and hangers), nonferrous components (such as wood), stainless steel, or steel with a minimum of G-90 hot-dipped galvanized coating are recommended. Additionally, access panels are recommended so components within soffit cavities can be periodically inspected for corrosion or dry rot.

Loads and Resistance

The IBC requires that soffits, exterior non-load-bearing walls, and wall coverings have sufficient strength to resist the positive and negative design wind pressures.

Soffits: Depending on the wind direction, soffits can experience either positive or negative pressure. Besides the cost of repairing the damaged soffits, wind-borne soffit debris can cause property damage and injuries. Failed soffits may also provide a convenient path for wind-driven rain to enter the building, as illustrated by Figure 6-55. This school had a steep-slope roof with a ventilated attic space. The exterior CMU/brick veneer wall stopped just above the soffit (red arrows at Figure 6-55). Wind-driven rain entered the attic space where the soffit had blown away. This and other storm-damage research has shown that water blown into attic spaces after the loss of soffits can cause significant damage and the collapse of ceilings. Even in instances where soffits remain in place, water can penetrate through soffit vents and cause damage.

Figure 6-55:
The exterior wall stopped just above the soffit (red arrows). After the metal soffit panels blew away, wind-driven rain blew into the attic space, which saturated the fiberglass batt insulation and caused the ceiling boards to collapse. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

For soffit design and application recommendations, see FEMA P-499, Fact Sheet 7.5, *Minimizing Water Intrusion Through Roof Vents in High-Wind Regions*, (2010), available at http://www.fema.gov/library/viewRecord.do?id=2138.

The 2010 edition of ASCE 7 added loading criteria for soffits. Section 30.9.3 states that pressures on soffits (referred to as "overhangs") are equal to the adjacent wall pressures. At this time, the only known test standard pertaining to soffit wind and wind-driven rain resistance is the Florida Building Code's *Testing Application Standard (TAS) No. 100(A)-95*. With this method, wind pressure testing is conducted to a maximum test speed of 140 mph, and wind-driven rain testing is conducted to a maximum test speed of 110 mph. The results of laboratory research have shown the need to develop an improved test method to evaluate the wind pressure and wind-driven rain resistance of soffits, but an improved test method has not yet been standardized.

Exterior non-load-bearing masonry walls: Particular care should be given to the design and construction of exterior non-load-bearing masonry walls. Although these walls are not intended to carry gravity loads, they should be designed to resist the external and internal loading for components and cladding in order to avoid collapse. When these types of walls collapse, they represent a severe risk to life because of their great weight.

Figure 6-56:
The red arrows show the original location of a CMU wall that nearly collapsed following a rolling door failure. Estimated wind speed: 140–160 mph. Hurricane Charley (Florida, 2004)

Interior non-load-bearing masonry walls: Special consideration should also be given to interior non-load-bearing masonry walls. Although these walls are not required by building codes to be designed to resist wind loads, if the exterior glazing is broken, or the exterior doors are blown away, the interior walls could be subjected to significant loads as the building rapidly becomes fully pressurized. To avoid casualties, it is recommended that interior non-load-bearing masonry walls adjacent to occupied areas be designed to accommodate loads exerted by a design wind event, using the partially enclosed pressure coefficient (see Figure 6-56). By doing so, wall collapse may be prevented if the building envelope is breached. This recommendation is applicable to schools that will be used as hurricane evacuation shelters, to schools located in areas with a basic wind speed greater than 165 mph,[21] and to schools in tornado-prone regions that do not have shelter space designed in accordance with FEMA 361.

21 The 165-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 120 mph.

Wall Coverings

Most schools do not have elevator penthouses. But for those that do, the penthouse walls must possess adequate wind and water resistance in order to ensure continuity of elevator service. If the walls blow away or water leaks through the wall system, the elevator controls and/or motors can be destroyed. Loss of elevators may affect facility operations. The restoration of elevator service can take weeks, even with expedited work.

There are a variety of exterior wall coverings. Brick veneer, exterior insulation finish systems (EIFS), stucco, metal wall panels, and aluminum and vinyl siding have often exhibited poor wind performance. Veneers (such as ceramic tile and stucco) over concrete, stone veneer, and cement-fiber panels and siding have also blown off. Wood siding and panels rarely blow off. Although tilt-up precast walls have failed during wind storms, precast wall panels attached to steel or concrete framed buildings typically offer excellent wind performance. The elevated school shown in Figure 6-57 had precast wall panels. The panels performed well, but portions of the roof covering blew off. Rooftop equipment also blew off. A gas line to one of the rooftop units was ruptured and displaced.

Figure 6-57: Although uncommon for schools, precast wall panels were attached to the structural frame of this school. This type of wall typically offers excellent wind performance. Note the roof covering damage and displaced gas line. Estimated wind speed: Approximately 125–130 mph. Hurricane Katrina (Louisiana, 2005)

Brick veneer: Brick veneer is frequently blown off walls during high winds. When brick veneer fails, wind-driven water can enter and damage buildings, and building occupants can be vulnerable to injury from wind-borne debris (particularly if the walls are sheathed with plastic foam insulation or wood fiberboard in lieu of wood panels). Pedestrians in the vicinity of damaged walls can also be vulnerable to injury from falling veneer. Common failure modes include tie (anchor) fastener pull-out, failure of masons to embed ties into the mortar (Figure 6-58), poor bonding between ties and mortar, a mortar of poor quality, and tie corrosion.

Figure 6-58: The four ties shown by the red arrows were not embedded into the mortar. Estimated wind speed: 105 mph. Hurricane Katrina, (Mississippi, 2005)

For brick veneer design and application recommendations, see FEMA P-499, Fact Sheet 5.4, *Attachment of Brick Veneer in High-Wind Regions,* (2010), available at http://www.fema.gov/library/viewRecord.do?id=2138.

Ties are often installed before brick laying begins. When this is done, ties are often improperly placed above or below the mortar joints. When misaligned, the ties must be angled up or down to be embedded into the mortar joints. Misalignment not only reduces the embedment depth, but also reduces the effectiveness of the ties, because wind forces do not act parallel to the ties themselves.

Corrugated ties typically used in residential veneer construction provide little resistance to compressive loads. The use of compression struts would likely be beneficial, but off-the-shelf devices do not currently exist. Two-piece adjustable ties provide significantly greater compressive strength than corrugated ties, and are therefore recommended.

To avoid water leaking into the building, it is important that weep holes be adequately spaced and not be blocked during brick installation, and that through-wall flashings be properly designed and installed. When the base of the brick veneer occurs near grade, the grade should be designed so that it occurs several inches below the weeps so that drainage from the weeps is not impeded. Also, landscaping should be kept clear of weeps so that vegetation growth does not cause blockage of weeps. At the building shown in Figure 6-59, water leaked into the building along the base of many of the brick veneer walls. When high winds accompany heavy rain, a substantial amount of water can be blown into the wall cavity.

EIFS: Figure 6-60 shows typical EIFS assemblies. Figure 6-61 shows EIFS blow-off. In this case, the molded expanded polystyrene (MEPS) was attached to gypsum board, which in turn was attached to metal studs. The gypsum board detached from the studs, which is a common EIFS failure mode. When the gypsum board on the exterior side of the studs is blown away, it is common for gypsum board on the interior side to also be blown off. The opening allows the building to become fully pressurized and allows the entrance of wind-driven rain. Other common types of failure include wall framing failure (see Figure 6-63), separation of the MEPS from its substrate, and separation of the synthetic stucco from the MEPS.

When EIFS is applied over a concrete or CMU wall, the concrete/CMU substrate normally prevents wind and water from entering a building. But if the EIFS debonds from the concrete/CMU, EIFS debris can break unprotected glazing.

Figure 6-59:
Water leaked inside along the base of the brick veneer walls (red arrow). Estimated wind speed: 115 mph. Hurricane Katrina (Louisiana, 2005)

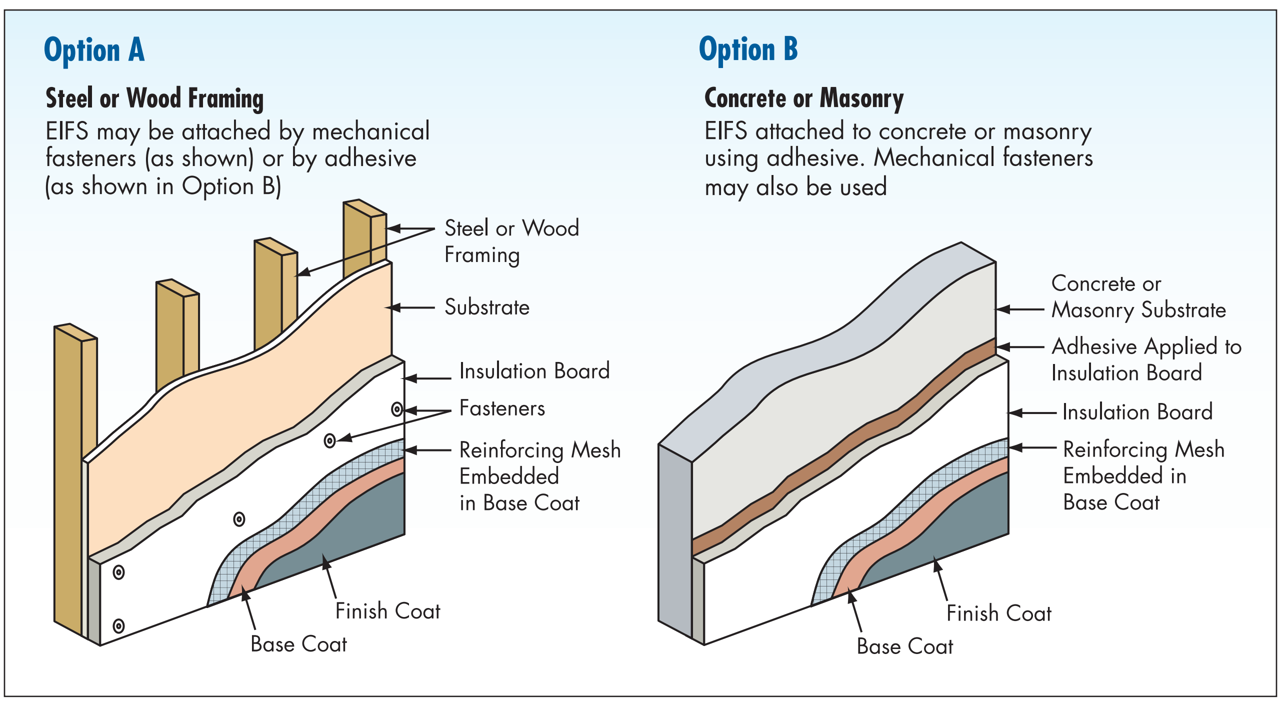


Figure 6-60: Typical EIFS assemblies

Figure 6-61:
EIFS blow-off near a wall corner. At one area, the metal fascia was also blown in.

SOURCE: FEMA 342, OKLAHOMA AND KANSAS MIDWEST TORNADOES OF MAY 3, 1999 (1999B)

Reliable wind performance of EIFS is very demanding on the designer and installer. It is particularly important to attach the gypsum board with a sufficient number of properly located fasteners and to properly apply the adhesive. At the newly constructed building shown in Figure 6-62, several of the gypsum boards blew off because of an inadequate number of screws. Also, at the gypsum board joint, there was insufficient fastener edge distance. Although not the primary failure mode, the adhesive between the MEPS and gypsum board was applied in rows, rather than continuously over the entire substrate with a notched trowel.

Figure 6-62:
At this EIFS failure, the screws attaching the gypsum board (yellow colored material) were too far apart (red circle). Additionally, at the board joint, the screws were too close to the board edge (blue circle). In this area, the screws were spaced at 4½, 4, 6, 6, 9, and 9½ inches on center. Also, the adhesive between the gypsum board and MEPS was applied in rows rather than continuously over the gypsum board. Estimated wind speed: 120 mph. Hurricane Katrina (Mississippi, 2005)

Maintenance of EIFS and associated sealant joints in order to minimize the reduction of EIFS' wind resistance due to water infiltration is also important. It is strongly recommended that EIFS be designed with a drainage system that allows for the dissipation of water leaks. For further information on EIFS performance during high winds and design guidance, see FEMA 489 and 549.

Another issue associated with EIFS is the potential for judgment errors. EIFS applied over studs is sometimes mistaken for a concrete wall, which people may seek shelter behind. However, instead of being protected by several inches of concrete, only two layers of gypsum board (i.e., one layer on each side of the studs) and a layer of MEPS separate the occupants from the impact of wind-borne debris that can easily penetrate such a wall and cause injury.

Stucco over studs: Wind performance of traditional stucco walls is similar to the performance of EIFS, as shown in Figure 6-63. In several areas the metal stud system failed, in other areas the gypsum sheathing blew off the studs, and in other areas, the metal lath blew off the gypsum sheathing. The failure shown in Figure 6-63 illustrates the importance of designing and constructing wall framing (including attachment of stud tracks to the building and attachment of the studs to the tracks) to resist the design wind loads.

Figure 6-63:
The stucco wall failure was caused by inadequate attachment between the stud tracks and the building's structure. All of the metal stud framing within the red oval blew away. The arrow shows a bottom stud track that detached and pulled away from the building. Estimated wind speed: 110–125 mph. Hurricane Ivan (Florida, 2004)

Metal wall panels: Wind performance of metal wall panels is highly variable. Performance depends on the strength of the specified panel (which is a function of material and thickness, panel profile, panel width, and whether the panel is a composite) and the adequacy of the attachment (which can be by either concealed clips or exposed fasteners). Excessive spacing between clips/fasteners is the most common problem. Clip/fastener spacing should be specified, along with the specific type and size of fastener. Figure 6-64 illustrates metal wall panel problems. At this school (which is also shown in Figure 6-12), the metal panels were attached with concealed fasteners. The panels unlatched at the standing seams. In addition to generating wind-borne debris, loss of panels allowed wind-driven rain to enter the building. Water entry was facilitated by lack of a moisture barrier and solid sheathing behind the metal panels (as discussed below).

Figure 6-64: The loss of metal wall panels allowed a substantial amount of wind-driven rain to penetrate into the classroom. Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida, 2004)

Metal wall panel performance also depends on adequacy of the framing to which it is attached. At the school shown in Figure 6-65, the metal fascia panels were attached to wood furring that was inadequately attached to CMU. Unlike the condition at the school shown at Figure 6-64, with the CMU behind the metal panels, water was prevented from entering the school. However, wind-borne fascia debris can cause damage or cause injury.

Figure 6-65: Blow-off of metal fascia panels due to inadequate attachment of wood furring to the CMU wall. Estimated wind speed: 85–95 mph. Hurricane Ivan (Florida, 2004)

To minimize water infiltration at metal wall panel joints, it is recommended that sealant tape be specified at sidelaps when the basic wind speed is in excess of 120 mph.[22] However, endlaps should be left unsealed so that moisture behind the panels can be wicked away. Endlaps should be a minimum of 3 inches (4 inches where the basic wind speed is greater than 165 mph[23]) to avoid wind-driven rain infiltration. At the base of the wall, a 3-inch (4-inch) flashing should also be detailed, or the panels should be detailed to overlap with the slab or other components by a minimum of 3 inches (4 inches).

Siding: Vinyl siding blow-off is typically caused by nails spaced too far apart and/or the use of vinyl siding that has inadequate wind resistance. Vinyl siding is available with enhanced wind resistance features, such as an enhanced nailing hem, greater interlocking area, and greater thickness. In high wind regions, fiber cement siding blow-off is typically caused by the use of blind nails rather than face nails (see Figure 6-66). Where the design wind speed is low enough to use blind nailing, if blow-off occurs, it is typically caused by nails spaced too far apart and/or too close to the edge of the siding. Wood siding generally performs well in high wind events.

22 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

23 The 165-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 120 mph.

Figure 6-66:
This cement fiber siding was attached with blind nails (red circle). Because of the high design wind speed, face nails should have been used (blue circle). Hurricane Francis (Florida, 2004)

Secondary line of protection: Almost all wall coverings permit the passage of some water past the exterior surface of the covering, particularly when the rain is wind-driven. For this reason, most wall coverings should be considered water-shedding, rather than waterproofing coverings. To avoid moisture-related problems, it is recommended that a secondary line of protection with a moisture barrier (such as housewrap or asphalt-saturated felt) and flashings around door and window openings be provided. Designers should specify that horizontal laps of the moisture barrier be installed so that water is allowed to drain from the wall (i.e., the top sheet should lap over the bottom sheet so that water running down the sheets remains on their outer surface). The bottom of the moisture barrier needs to be designed to allow drainage. Had the metal wall panels shown in Figure 6-64 been applied over a moisture barrier and sheathing, the amount of water entering the school would have likely been eliminated or greatly reduced, as is the case with the school shown in Figure 6-65.

For siding design and application recommendations, see FEMA P-499, Fact Sheet 5.3, *Siding Installation in High-Wind Regions,* (2010), available at http://www.fema.gov/library/viewRecord.do?id=2138.

In areas that experience frequent wind-driven rain, incorporating a pressure-equalized rain screen design, by installing vertical furring strips between the moisture barrier and siding materials, will facilitate drainage of water from the space between the moisture barrier and backside of the siding. (For further information on rain screen wall systems, see the Siding Advisory.) In areas that frequently experience strong winds, enhanced flashing is recommended. Enhancements include use of flashings that have extra-long flanges, and the use of sealant and tapes. Flashing design should recognize that wind-driven water could be pushed up vertically. The height to which water can be pushed increases with wind speed. Water can also migrate vertically and horizontally by capillary action between layers of materials (e.g., between a flashing flange and housewrap). Use of a rain screen design, in conjunction with enhanced flashing design, is recommended in areas that frequently experience wind-driven rain or strong winds. It is recommended that designers attempt to determine what type of flashing details have successfully been used in the area where the facility will be constructed.

Underside of Elevated Floors

- If sheathing is applied to the underside of joists or trusses elevated on piles (e.g., to protect insulation installed between the joists/trusses), its attachment should be specified in order to avoid blow-off. Stainless steel or hot-dip galvanized nails or screws are recommended. Since ASCE 7 does not provide guidance for load determination, professional judgment in specifying attachment is needed.

6.3.3.5 Non-Load-Bearing Walls, Wall Coverings, and Soffits in Hurricane-Prone Regions

To minimize long-term problems with exterior wall coverings and soffits, it is recommended that they be avoided to the maximum extent possible. Exposed or painted reinforced concrete or CMU offers greater reliability (i.e., they have no coverings that can blow off and become wind-borne debris).

For interior non-load-bearing masonry walls in schools located where the basic wind speed is greater than 165 mph, see the recommendations given in Section 6.3.3.4.[24]

24 The 165-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 120 mph

6.3.3.6 Roof Systems

For further general information on roof systems, see the National Institute of Building Sciences' *Building Envelope Design Guide* (www.wbdg.org/design/envelope.php).

Because roof covering damage has historically been the most frequent and the costliest type of wind damage, special attention needs to be given to roof system design. See Section 6.3.3.7 for additional information pertaining to schools located in hurricane-prone regions.

Code Requirements

The IBC requires the load resistance of the roof assembly to be evaluated by one of the test methods listed in IBC's Chapter 15. Design professionals are cautioned that designs that deviate from the tested assembly (either with material substitutions or change in thickness or arrangement) may adversely affect the wind performance of the assembly. The IBC does not specify a minimum safety factor. However, for the roof system, a safety factor of 2 is recommended. To apply the safety factor, divide the test load by 2 to determine the allowable design load. Conversely, multiply the design load by 2 to determine the minimum required test resistance.

The roof of the elevator penthouse must possess adequate wind and water resistance to ensure continuity of elevator service. It is recommended that a secondary roof membrane, as discussed in Section 6.3.3.7, be specified over the elevator penthouse roof deck.

The Design Load when using allowable stress design:

When using ASCE 7-05 and earlier editions, the design load is the load derived from the calculation procedure given in Chapter 6.

When using ASCE 7-10, the design load is the load derived from the calculation procedure given in Chapter 30, which is then multiplied by 0.6 (the load combination factor given in Section 2.4.1).

For structural metal panel systems, the IBC requires test methods UL 580 or ASTM E 1592. It is recommended that design professionals specify use of E 1592, because it gives a better representation of the system's uplift performance capability. At the building shown in Figure 6-67, three of the standing seams opened up (unlatched). In the opened condition, the panels were very susceptible to progressive failure, and they were no longer in a watertight condition. At other roof areas, several panels were blown off. ASTM E 1592 is more suitable than UL 580 for assessing the potential for panels to unlatch. Note the air terminal ("lightning rod") shown by the red arrow. The lightning protection system (LPS) conductor ran underneath the ridge flashing. By being concealed underneath the ridge flashing, the conductor was shielded from the wind, (as recommended in Section 6.3.4.4) and was therefore not susceptible to blow-off.

Figure 6-67:
Three of the panel ribs opened up (one to the right of the blue arrow and two to the left). The LPS conductor serving the air terminal (red arrow) ran underneath the ridge flashing. Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida, 2004)

Load Resistance

Load resistance is commonly specified by a Factory Mutual Research (FMR) rating, such as FM 1-75. The first number (1) indicates that the roof assembly passed the FMR tests for a Class 1 fire rating. The second number (75) indicates the uplift resistance in pounds per square foot (psf) that the assembly achieved during testing. With a safety factor of two this assembly would be suitable for a maximum design uplift load of 37.5 psf.

The highest uplift load occurs at the roof corners because of building aerodynamics as discussed in Section 6.1.3. The perimeter has a somewhat lower load, while the field of the roof has the lowest load. FMG Property Loss Prevention Data Sheets (dates vary) are formatted so that a roof assembly can be selected for the field of the roof. For the perimeter and corner areas, FMG Data Sheet 1-29 provides three options: 1) use the FMG *Approval Guide* listing if it includes a perimeter and corner fastening method; 2) use a roof system with the appropriate FMG Approval rating in the field, perimeter, and corner, in accordance with Table 1 in FMG Data Sheet 1-29; or 3) use prescriptive recommendations given in FMG Data Sheet 1-29.

FM Global (FMG) is the name of the Factory Mutual Insurance Company and its affiliates. One of FMG's affiliates, Factory Mutual Research (FMR) provides testing services, produces documents that can be used by designers and contractors, and develops test standards for construction products and systems. FMR evaluates roofing materials and systems for resistance to fire, wind, hail, water, foot traffic, and corrosion. Roof assemblies and components are evaluated to establish acceptable levels of performance. Some documents and activities are under the auspices of FMG and others are under FMR.

Although other test labs can test systems using FMG test methods, in order to achieve FMG approval, system testing must be conducted by FMG. Roof assemblies that meet FMG requirements can be found at https://roofnav.fmglobal.com/RoofNav/Login.aspx.

FMG's Loss Prevention Data Sheets can be downloaded from the above Web site. The Data Sheets are not updated on a regular basis. Refer to the Web site to ensure that the current edition is being used.

When perimeter and corner uplift resistance values are based on a prescriptive method rather than testing, the field assembly is adjusted to meet the higher loads in the perimeter and corners by increasing the number of fasteners or decreasing the spacing of adhesive ribbons by a required amount. However, this assumes that the failure is the result of the fastener pulling out from the deck, or that the failure is in the vicinity of the fastener plate, which may not be the case. Also, the increased number of fasteners required by FMG may not be sufficient to comply with the perimeter and corner loads derived from the building code. Therefore, if FMG resistance data are specified, it is prudent for the design professional to specify the resistance for each zone of the roof separately. Using the example cited above, if the field of the roof is specified as 1-75, the perimeter would be specified as 1-130 and the corner would be specified as 1-190.

If the roof system is fully adhered, it is not possible to increase the uplift resistance in the perimeter and corners. Therefore, for fully adhered systems, the uplift resistance requirement should be based on the corner load rather than the field load.

Roof System Performance

Storm-damage research has shown that sprayed polyurethane foam (SPF) and liquid-applied roof systems are very reliable high-wind performers. If the substrate to which the SPF or liquid-applied membrane is applied does not lift, it is highly unlikely that these systems will blow off. Both systems are also more resistant to leakage after missile impact damage than most other systems. Built-up roofs (BURs) and modified bitumen systems have also demonstrated good wind performance provided the edge flashing/coping does not fail (which happens frequently). The exception is aggregate surfacing, which is prone to blow-off (see Figures 6-14, 6-23, and 6-53). Modified bitumen applied to a concrete deck has demonstrated excellent resistance to progressive peeling after blow-off of the metal edge flashing. Metal panel performance is highly variable. Some systems are very wind resistant, while others are quite vulnerable.

Of the single-ply attachment methods, the paver-ballasted and fully adhered methods are the least problematic. Systems with aggregate ballast are prone to blow-off, unless care is taken in specifying the size of aggregate and the parapet height (see Figures 6-8 and 6-53). The performance of protected membrane roofs (PMRs) with a factory-applied cementitious coating over insulation boards is highly variable. When these boards are installed over a loose-laid membrane, it is critical that an air retarder be incorporated to prevent the membrane from ballooning and disengaging the boards. ANSI/SPRI RP-4 (which is referenced in the IBC) provides wind guidance for ballasted systems using aggregate, pavers, and cementitious-coated boards.

When fully adhering insulation boards, it is recommended that the boards be no larger than 4 feet by 4 feet. It is also recommended that the board thickness not exceed 2 inches (1½ inches is preferable). Use of small thin boards makes it easier for the contractor to conform the boards to the substrate. At the building shown in Figure 6-68, 4-foot by 8-foot insulation boards were set in hot asphalt over a concrete deck. A few of the boards detached from the deck. The boards may have initiated the membrane blow-off, or the membrane blow-off may have been initiated by lifting and peeling of the metal edge flashing, in which case, loss of the insulation boards was a secondary failure.

When fully adhering boards to concrete decks, it is recommended that a planar flatness of a maximum of ¼-inch variation over a 10-foot length (when measured by a straightedge) be specified. Prior to installation of the roof insulation, it is recommended that the planar flatness be checked with a straightedge. If the deck is outside of the ¼-inch variation, it is recommended that the high spots be ground or the low spots be suitably filled.

The *Wind Design Guide for Mechanically Attached Flexible Membrane Roofs*, B1049 (National Research Council of Canada, 2005) provides recommendations related to mechanically attached single-ply and modified bituminous systems. B1049 is a comprehensive wind design guide that includes discussion on air retarders. Air retarders can be effective in reducing membrane flutter, in addition to being beneficial for use in ballasted single-ply systems. When a mechanically attached system is specified, careful coordination with the structural engineer in selecting deck type and thickness is important.

Figure 6-68: The blown off insulation (red arrow) may have initiated blow-off of the roof membrane. Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida, 2004)

For metal panel and metal shingle roof system design and application recommendations, FEMA P-499, Fact Sheet 7.6, *Metal Roof Systems in High-Wind Regions,* (2010), is available at http://www.fema.gov/library/viewRecord.do?id=2138.

When specifying a mechanically attached single-ply membrane, if a steel deck is selected, it is critical to specify that the membrane fasteners be attached in rows perpendicular to the steel flanges to avoid overstressing the attachment of the deck to the deck support structure. At the school shown in Figure 6-69, the fastener rows of the mechanically attached single-ply membrane ran parallel to the top flange of the steel deck. The deck fasteners were overstressed and a portion of the deck blew off and the membrane progressively tore. When membrane fasteners run parallel to the flange, the flange with membrane fasteners essentially carries the entire uplift load because of the deck's inability to transfer any significant load to adjacent flanges. Hence, at the joists shown in Figure 6-68, the deck fasteners on either side of the flange with the membrane fasteners are the only connections to the joist that are carrying substantial uplift load.

Figure 6-69:
The orientation of the membrane fastener rows led to blow-off of the steel deck. Hurricane Marilyn (U.S. Virgin Islands, 1995)

Edge Flashings and Copings

Roof membrane blow-off is almost always a result of lifting and peeling of the metal edge flashing or coping, which serves to clamp down the membrane at the roof edge. Therefore, it is important for the design professional to carefully consider the design of metal edge flashings, copings, and the nailers to which they are attached. The metal edge flashing on the modified bitumen membrane roof shown in Figure 6-70 was installed underneath the membrane, rather than on top of it, and then stripped in. In this location, the edge flashing was unable to clamp the membrane down. At one area, the membrane was not sealed to the flashing. An ink pen was inserted into the opening prior to photographing to demonstrate how wind could catch the opening and lift and peel the membrane.

Figure 6-70: The ink pen shows an opening that the wind can catch to cause lifting and peeling of the membrane.

ANSI/SPRI ES-1 provides general design guidance including a methodology for determining the outward-acting load on the vertical flange of the flashing/coping (ASCE 7 does not provide this guidance). ANSI/SPRI ES-1 is referenced in the IBC. ANSI/SPRI ES-1 also includes test methods for assessing flashing/coping resistance. This manual recommends a minimum safety factor of 3 for edge flashings, copings, and nailers for schools. For FMG-insured facilities, FMR-approved flashing should be used and FM Data Sheet 1-49 should also be consulted.

The traditional edge flashing/coping attachment method relies on concealed cleats that can deform under wind load and lead to disengagement of the flashing/coping (see Figure 6-71) and subsequent lifting and peeling of the roof membrane. When a vertical flange disengages and lifts up, the edge flashing and membrane are very susceptible to failure. Normally, when a flange lifts, the failure continues to propagate and the metal edge flashing and roof membrane blows off.

Figure 6-71:
The metal edge flashing on this building disengaged from the continuous cleat and the vertical flange lifted. Hurricane Hugo (South Carolina, 1989)

At the building shown in Figure 6-72, the cleat nailing provided very little resistance to outward deflection of the cleat and coping. While most of the continuous inner and outer cleats remained on the building, several sections of coping and at least one cleat blew off once the amount of deflection was sufficient for the coping to disengage from the cleat. In this case, the roof membrane did not lift and peel as often happens when the coping blows off. However, the coping debris did gouge the roof membrane. Note that the base flashing was stopped at the top of the parapet. It should have been run across the top of the nailer and turned down and nailed so as to provide greater watertight protection in the event of coping leakage or coping blow-off.

Figure 6-72:
The coping blew off because of inadequate attachment of the cleats. Estimated wind speed: 92 mph. Hurricane Ike (Texas, 2008)

Storm-damage research has revealed that, in lieu of cleat attachment, the use of exposed fasteners to attach the vertical flanges of copings and edge flashings is a very effective and reliable attachment method. The coping shown in Figure 6-73 was attached with ¼-inch diameter stainless steel concrete spikes at 12 inches on center. When the fastener is placed in wood, #12 stainless steel screws with stainless steel washers are recommended. The fasteners should be more closely spaced in the corner areas (the spacing will depend upon the design wind loads). ANSI/SPRI ES-1 provides guidance on fastener spacing and thickness of the coping and edge flashing.

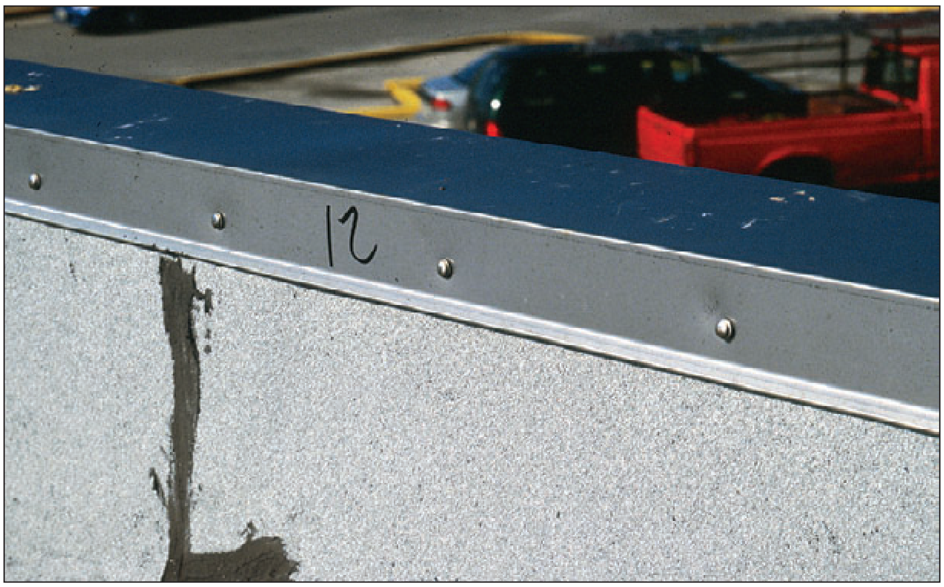


Figure 6-73:
Both vertical faces of the coping were attached with exposed fasteners instead of concealed cleats. Typhoon Paka (Guam, 1997)

Gutters and Downspouts

Storm-damage research has shown that gutters are seldom designed and constructed to resist wind loads. At the school shown in Figure 6-74, the gutter brackets were attached with a fastener near the top and bottom of the bracket. Hence, the fasteners prevented the brackets from rotating out from the wall. However, because the gutter was not attached to the brackets, the gutter blew away. When a gutter lifts, it typically causes the edge flashing that laps into the gutter to lift as well. Frequently, this results in a progressive lifting and peeling of the roof membrane. The membrane blow-off shown in Figure 6-75 was initiated by gutter uplift. The gutter was similar to that shown in Figure 6-74. The membrane blow-off caused significant interior water damage.

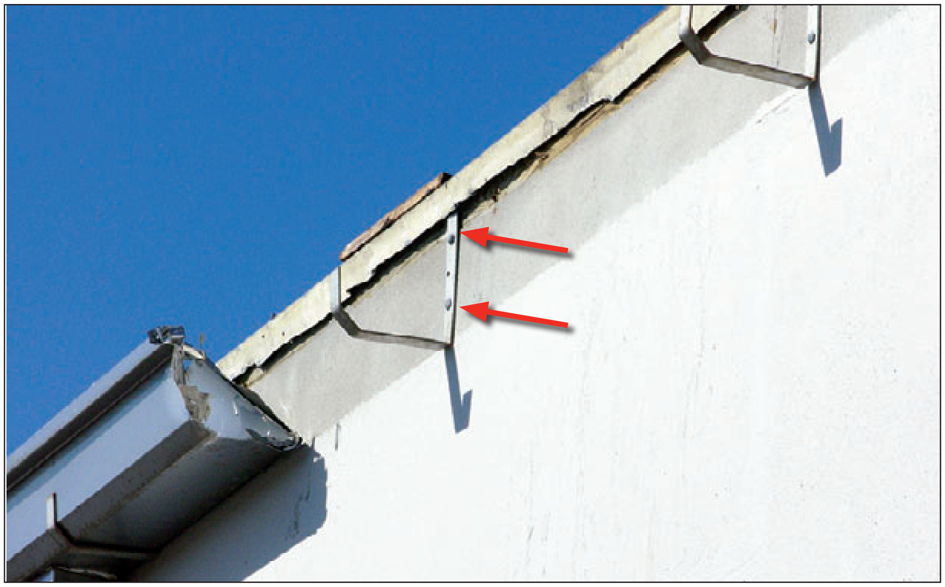


Figure 6-74: Because this gutter was not attached to the bracket, wind lifted the gutter along with the metal edge flashing that lapped into the gutter. Bracket fasteners are indicated by the red arrows. Hurricane Francis (Florida, 2004)

Figure 6-75: The original modified bitumen membrane was blown away after the gutter lifted in the area shown by the red arrow (the black membrane is a temporary roof). Hurricane Francis (Florida, 2004)

Special design attention needs to be given to attaching gutters to prevent uplift, particularly for those in excess of 6 inches in width. Currently, there are no design guides or standards pertaining to gutter wind resistance. It is recommended that the designer calculate the uplift load on gutters using the overhang coefficient from ASCE 7. There are two approaches to resist gutter uplift.

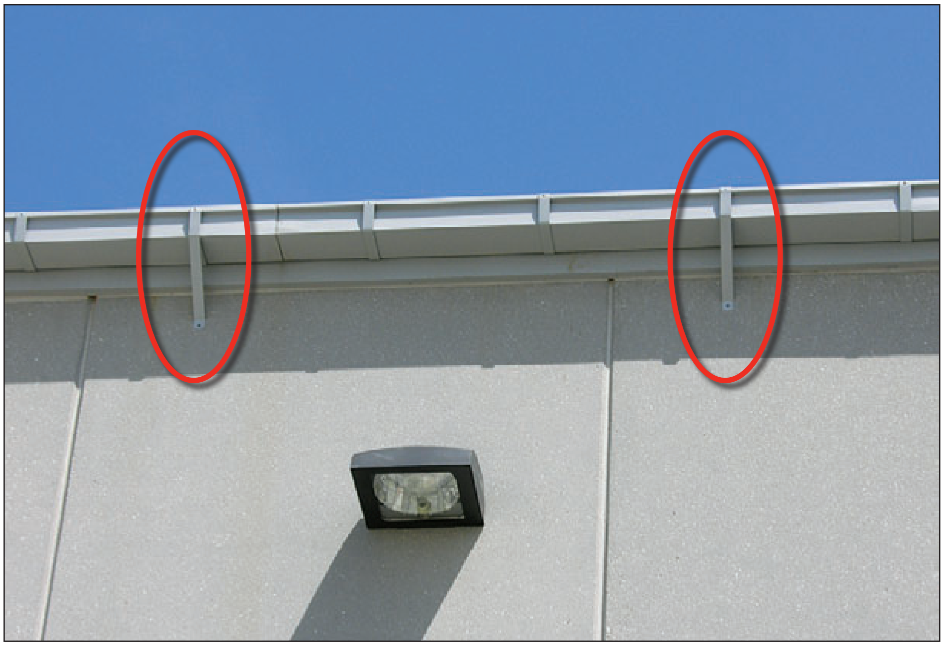
- Gravity-support brackets can be designed to resist uplift loads. In these cases, in addition to being attached at its top, the bracket should also be attached at its low end to the wall (as was the case for the brackets shown in Figure 6-74). The gutter also needs to be designed so it is attached securely to the bracket in a way that will effectively transfer the gutter uplift load to the bracket (see Figure 6-76). Bracket spacing will depend on the gravity and uplift load, the bracket's strength, and the strength of connections between the gutter/bracket and the bracket/wall. With this option, the bracket's top will typically be attached to a wood nailer, and that fastener will be designed to carry the gravity load. The bracket's lower connection will resist the rotational force induced by gutter uplift. Because brackets are usually spaced close together to carry the gravity load, developing adequate connection strength at the lower fastener is generally not difficult. Screws rather than nails are recommended to attach brackets to the building because screws are more resistant than nails to dynamically induced pull-out forces.

Figure 6-76:
At this gutter, a fastener connected the bracket to the gutter. Note: To avoid leakage at the fasteners between the bracket and gutter, the bracket should extend near or to the top of the gutter so that the fastener would be above the waterline. Estimated wind speed: 95 mph. Hurricane Ike (Texas, 2008)

- The other option is to use gravity-support brackets only to resist gravity loads, and use separate sheet-metal straps at 45-degree angles to the wall to resist uplift loads (Figure 6-77). Strap spacing will depend on the gutter uplift load and strength of the connections between the gutter/strap and the strap/wall. Note that FMG Data Sheet 1-49 recommends placing straps 10 feet apart. However, at that spacing with wide gutters, fastener loads induced by uplift are quite high. When straps are spaced at 10 feet, it can be difficult to achieve sufficiently strong uplift connections.

When designing a bracket's lower connection to a wall or a strap's connection to a wall, designers should determine appropriate screw pull-out values. With this option, a minimum of two screws at each end of a strap is recommended. At a wall, screws should be placed side by side, rather than vertically aligned, so the strap load is carried equally by the two fasteners. When fasteners are vertically aligned, most of the load is carried by the top fastener.

Figure 6-77: Sheet metal straps were attached to an existing gutter that lacked sufficient uplift resistance.



Since the uplift load in the corners is much higher than the load between the corners, enhanced attachment is needed in corner areas regardless of the option chosen. ASCE 7 provides guidance about determining a corner area's length.

Storm damage research has also shown that downspouts are seldom designed and constructed to resist wind loads (see Figure 6-78). Special design attention needs to be given to attaching downspouts to prevent blow-off. Currently there are no design guides or standards pertaining to downspout wind resistance. The keys to achieving successful performance include providing brackets that are not excessively spaced, bracket strength, and the strength of the connections between the brackets and wall.

Parapet Base Flashings

Information on loads for parapet base flashings was first introduced in the 2002 edition of ASCE 7. The loads on base flashings are greater than the loads on the roof covering if the parapet's exterior side is air-permeable. When base flashing is fully adhered, it has sufficient wind resistance in most cases. However, when base flashing is mechanically fastened, typical fastening patterns may be inadequate, depending on design wind conditions (see Figure 6-79). Therefore, it is imperative that the base flashing loads be calculated, and attachments be designed to accommodate these loads. It is also important for designers to specify the attachment spacing in parapet corner regions to differentiate them from the regions between corners.

Figure 6-78: Blow-off of this downspout resulted in glazing breakage. Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida, 2004)

Figure 6-79: If mechanically attached base flashings have an insufficient number of fasteners, the base flashing can be blown away. Hurricane Andrew (Florida, 2004)

When the roof membrane is specified to be adhered, it is recommended that fully adhered base flashings be specified in lieu of mechanically attached base flashings. Otherwise, if the base flashing is mechanically attached, ballooning of the base flashing during high winds can lead to lifting and progressive peeling of the roof membrane.

Steep-Slope Roof Coverings

For a discussion of wind performance of asphalt shingle (see Figure 6-12) and tile roof coverings (see Figure 6-83), see FEMA 488, FEMA 489, FEMA 549, and FEMA P-757. For recommendations pertaining to asphalt shingles and tiles, see Fact Sheets 7.1, 7.2, and 7.3 in FEMA P-499.

> For design and application recommendations pertaining to roof vents, see FEMA P-499, Fact Sheet 7.5, *Minimizing Water Intrusion Through Roof Vents in High-Wind Regions,* (2010), available at http://www.fema.gov/library/viewRecord.do?id=2138.

6.3.3.7 Roof Systems in Hurricane-Prone Regions

The following types of roof systems are recommended for schools in hurricane-prone regions, because they are more likely to avoid water infiltration if the roof is hit by wind-borne debris, and also because these systems are less likely to become sources of wind-borne debris:

- In tropical climates where insulation is not needed above the roof deck, specify either liquid-applied membrane over cast-in-place concrete deck, or modified bitumen membrane torched directly to primed cast-in-place concrete deck.
- Install a secondary membrane over a concrete deck (if another type of deck is specified, a cover board may be needed over the deck). Seal the secondary membrane at perimeters and penetrations. Specify rigid insulation over the secondary membrane. Where the basic wind speed is up to 150 mph,[25] a minimum 2-inch thick layer of insulation is recommended. Where the speed is between 150 and 175 mph,[26] a total minimum thickness of 3 inches is recommended (installed in two layers). Where the speed is greater than 175 mph, a total minimum thickness of 4 inches is recommended (installed in two layers). A layer of ⅝-inch thick glass mat gypsum roof board is recommended over the insulation, followed by a modified bitumen membrane. A modified bitumen membrane is recommended for the primary membrane because of its somewhat enhanced resistance to puncture by small missiles compared with other types of roof membranes.

25 The 150-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 110 mph.

26 The 150- to 175-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is between 110 and 130 mph.

The purpose of the insulation and gypsum roof board is to absorb missile energy. If the primary membrane is punctured or blown off during a storm, the secondary membrane should provide watertight protection unless the roof is hit with missiles of very high momentum that penetrate the insulation and secondary membrane. Figure 6-80 illustrates the merit of specifying a secondary membrane. Although the copper roof blew off, fortunately there was a very robust underlayment (a built-up membrane) that remained in place. The minor leakage that occurred did not impair building operations.

Figure 6-80: The secondary membrane prevented significant leakage into the building after the copper roof blew off. Hurricane Andrew (Florida, 1992)

For an SPF roof system over a concrete deck (if another type of deck is specified, a cover board may be needed over the deck), where the basic wind speed is less than 175 mph,[27] it is recommended that the foam be a minimum of 3 inches thick to avoid missile penetration through the entire layer of foam. Where the speed is greater than 175 mph, a 4-inch minimum thickness is recommended. It is also recommended that the SPF be coated, rather than protected with an aggregate surfacing.

With respect to wind-borne debris, SPF behaves quite differently than other types of roof coverings. Except for paver-ballasted systems, other types of coverings (including tough membranes such as modified bitumen and metal panels) can be easily penetrated by debris. When these other types of coverings are punctured, water enters the roof system and typically leaks into the building unless there is a secondary membrane.

27 The 175-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 130 mph.

With SPF, missiles can gouge the foam (as shown in Figure 6-81), but it is rare for missiles to completely penetrate through the foam. When a quality SPF is gouged, only an insignificant amount of moisture is absorbed into the foam cells at the gouged area, even if the gouge is not repaired for several months.

Figure 6-81: Although a missile cut into the SPF, the roof was still watertight. The ink pen (blue arrow) shows the relative size of the impact area. Estimated wind speed: 110 mph. Hurricane Ike (Texas, 2008)

- For a PMR, it is recommended that pavers weighing a minimum of 22 psf be specified. In addition, base flashings should be protected with metal (such as shown in Figure 6-88) to provide debris protection. Parapets with a 3-foot minimum height (or higher if so indicated by ANSI/SPRI RP-4) are recommended at roof edges. This manual recommends that PMRs not be used for schools in hurricane-prone regions where the basic wind speed exceeds 175 mph.[28]
- For structural metal roofs, it is recommended that a roof deck be specified, rather than attaching the panels directly to purlins as is commonly done with pre-engineered metal buildings. If panels blow off buildings without roof decking, wind-borne debris and rain are free to enter the building.

  Structural standing seam metal roof panels with concealed clips and mechanically seamed ribs spaced at 12 inches on center are recommended. If the panels are installed over a concrete deck, a modified bitumen secondary membrane is recommended if the deck has a slope less than ½:12. If the panels are installed over

28 The 175-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 130 mph.

a steel deck or wood sheathing, a modified bitumen secondary membrane (over a suitable cover board when over steel decking) is recommend, followed by rigid insulation and metal panels. Where the basic wind speed is up to 150 mph,[29] a minimum 2-inch thick layer of insulation is recommended. Where the speed is between 150 and 175 mph,[30] a total minimum thickness of 3 inches is recommended. Where the speed is greater than 175 mph, a total minimum thickness of 4 inches is recommended. Although some clips are designed to bear on insulation, it is recommended that the panels be attached to wood nailers attached to the deck, because nailers provide a more stable foundation for the clips.

If the metal panels are blown off or punctured during a hurricane, the secondary membrane should provide watertight protection unless the roof is hit with missiles of very high momentum. At the roof shown in Figure 6-82, the structural standing seam panel clips bore on rigid insulation over a steel deck. Had a secondary membrane been installed over the steel deck, the membrane would have likely prevented significant interior water damage and facility disruption.

Figure 6-82: Significant interior water damage and facility interruption occurred after the standing seam roof blew off. Hurricane Marilyn (U.S. Virgin Islands, 1995)

29 The 150-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 110 mph.

30 The 150- to 175-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is between 110 and 130 mph.

Based on field performance of architectural metal panels in hurricane-prone regions, exposed fastener panels are recommended in lieu of architectural panels with concealed clips. For panel fasteners, stainless steel screws are recommended. A secondary membrane protected with insulation is recommended, as discussed above for structural standing seam systems.

In order to avoid the possibility of roofing components blowing off and causing damage to other portions of the school or striking people arriving at a school shelter during a storm, the following roof systems are not recommended: aggregate surfacings, either on BUR, single-plies, or SPF; lightweight concrete pavers; cementitious-coated insulation boards; slate; and tile (see Figures 6-83 and 6-84). Even when slates and tiles are properly attached to resist wind loads, their brittleness makes them vulnerable to breakage as a result of wind-borne debris impact. The tile and slate fragments can be blown off the roof, and fragments can damage other parts of the roof causing a cascading failure.

The tiles shown in Figure 6-83 were attached with the foam-adhesive (adhesive-set) method. The tiles shown in Figure 6-84 were attached with the wire-tied method (an uncommon method in the eastern portion of the United States). In addition to the wire attachments, the tiles were also attached with stainless steel clips at the first three rows from the eave. All of the tiles had tail hooks, and adhesive was used between the tail and head of all tiles. Except for the three perimeter rows which were clipped, the wires did not prevent the tiles from lifting a short distance above the concrete deck. The failure was attributed to tiles lifting and then slamming back down on the deck, where upon they broke and the tile fragments blew away.

Figure 6-83: Brittle roof coverings, like slate and tile, can be broken by missiles, and tile debris can break other tiles. Estimated wind speed: 140–160 mph. Hurricane Charley (Florida, 2004)

Figure 6-84
These wire-tied tiles were installed over a concrete deck. The failure was attributed to lack of vertical restraint, which allowed the tiles to lift and then be broken when they slammed back down onto the deck. Typhoon Paka (Guam, 1997)

Mechanically attached and air-pressure equalized single-ply membrane systems are susceptible to massive progressive failure after missile impact, and are therefore not recommended for schools in hurricane-prone regions. At the school shown in Figure 6-85, a missile struck the fully adhered low-sloped roof and slid into the steep-sloped reinforced mechanically attached single-ply membrane in the vicinity of the red arrow. A large area of the mechanically attached membrane was blown away as a result of progressive membrane tearing. Fully adhered single-ply membranes are very vulnerable to missile puncture and are not recommended unless they are ballasted with pavers.

Figure 6-85: This mechanically attached single-ply membrane progressively tore after being cut by wind-borne debris. Hurricane Andrew (Florida, 1992)

Edge flashings and copings: If cleats are used for attachment, it is recommended that a "peel-stop" bar be placed over the roof membrane near the edge flashing/coping, as illustrated in Figure 6-86. The purpose of the bar is to provide secondary protection against membrane lifting and peeling in the event that edge flashing/coping fails. A robust bar specifically made for bar-over mechanically attached single-ply systems is recommended. The bar needs to be very well anchored to the parapet or the deck. Depending on design wind loads, spacing between 4 and 12 inches on center is recommended. A gap of a few inches should be left between each bar to allow for water flow across the membrane. After the bar is attached, it is stripped over with a stripping ply.

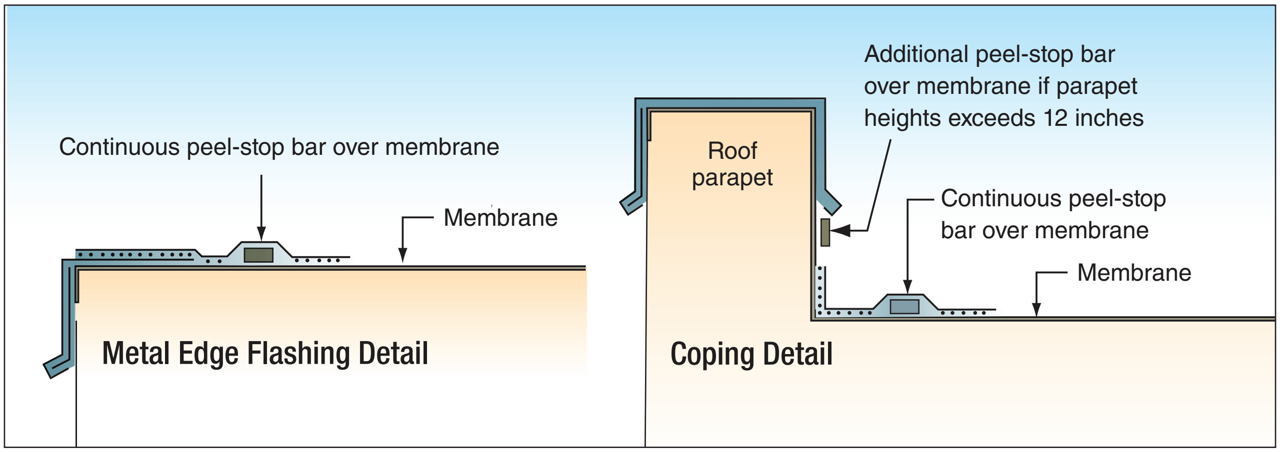


Figure 6-86: A continuous peel-stop bar over the membrane may prevent a catastrophic progressive failure if the edge flashing or coping is blown off. (Modified from FEMA 55, 2000)

Walkway pads: Roof walkway pads are frequently blown off during hurricanes (Figure 6-87). Pad blow-off does not usually damage the roof membrane. However, wind-borne pad debris can damage other building components and injure people. Currently there is no test standard to evaluate uplift resistance of walkway pads. Walkway pads are therefore not recommended in hurricane-prone regions.

Parapets: For low-sloped roofs, minimum 3-foot high parapets are recommended. With parapets of this height or greater, the uplift load in the corner region is substantially reduced (ASCE 7 permits treating the corner zone as a perimeter zone). Also, a high parapet (as shown in Figure 6-106) may intercept wind-borne debris and keep it from blowing off the roof and damaging other building components or injuring people. To protect base flashings from wind-borne debris damage and subsequent water leakage, it is recommended that metal panels on furring strips be installed over the base flashing (Figure 6-88). Exposed stainless steel screws are recommended for attaching the panels to the furring strips, because using exposed fasteners is more reliable than using concealed fasteners or clips (as were used for the failed panels shown in Figure 6-64).

Figure 6-87:
Several rubber walkway pads were blown off the single-ply membrane roof. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

Figure 6-88:
Base flashing protected by metal wall panels attached with exposed screws. Estimated wind speed: 120 mph. Hurricane Katrina (Mississippi, 2005)

6.3.4 Nonstructural Systems and Equipment

Nonstructural systems and equipment include all components that are not part of the structural system or building envelope. Exterior-mounted mechanical equipment (e.g., exhaust fans, HVAC units, relief air hoods, rooftop ductwork, and boiler stacks), electrical equipment (e.g., light fixtures and LPSs), and communications equipment (e.g., antennae and satellite dishes) are often damaged during high winds. Damaged equipment can impair the operation of the facility, the equipment can detach and become wind-borne missiles, and water can enter the facility where equipment was displaced (see Figure 6-89). The most common problems typically relate to inadequate equipment anchorage, inadequate strength of the equipment itself, and corrosion.

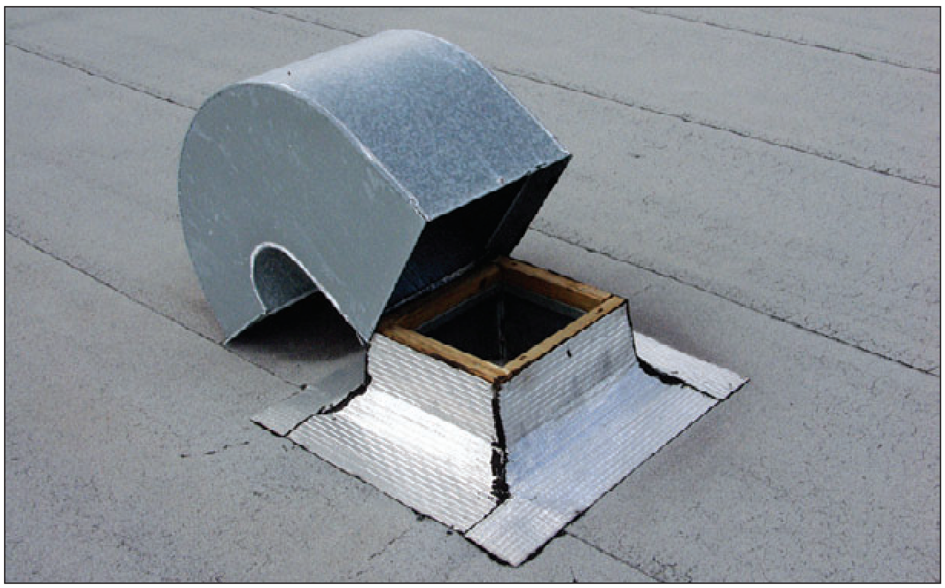


Figure 6-89: This gooseneck was attached with only two small screws. Emergency repairs had not been made at the time this photograph was taken, which was 5 days after the hurricane struck. A substantial amount of water was able to enter the school. Hurricane Francis (Florida, 2004)

Exterior-mounted equipment is especially vulnerable to hurricane-induced damage, and special attention should be paid to positioning and mounting of these components in hurricane-prone regions. See Sections, 6.3.4.2 and 6.3.4.4 for additional information pertaining to schools located in hurricane-prone regions.

6.3.4.1 Exterior-Mounted Mechanical Equipment

This section discusses loads and attachment methods, as well as the problems of corrosion and water infiltration.

Loads and Attachment Methods

Information on loads on rooftop equipment was first introduced in the 2002 edition of ASCE 7. For guidance on load calculations, see *Calculating Wind Loads and Anchorage Requirements for Rooftop Equipment*

(ASHRAE, 2006). A minimum safety factor of 3 is recommended for schools. Loads and resistance should also be calculated for heavy pieces of equipment since the dead load of the equipment is often inadequate to resist the design wind load. The 30-foot by 10-foot by 8-foot 18,000-pound HVAC unit shown in Figure 6-90 was attached to its curb with 16 straps (one screw per strap). Although the wind speeds were estimated to be only 85 to 95 miles per hour (peak gust), the HVAC unit blew off the building. The inset at Figure 6-90 shows the curb upon which the unit was attached. A substantial amount of water entered the building at the curb openings before the temporary tarp was placed.

Mechanical penetrations through the elevator penthouse roof and walls must possess adequate wind and water resistance to ensure continuity of elevator service (see Section 6.3.3.4). In addition to paying special attention to equipment attachment, air intakes and exhausts should be designed and constructed to prevent wind-driven water from entering the penthouse.


Figure 6-90:
Although this 18,000-pound HVAC unit was attached to its curb with 16 straps, it blew off the building during Hurricane Ivan. (Florida, 2004)

To anchor fans, small HVAC units, and relief air hoods, the minimum attachment schedule provided in Table 6-1 is recommended. The attachment of the curb to the roof deck also needs to be designed and constructed to resist wind loads. The cast-in-place concrete curb shown in Figure 6-91 was cold-cast over a concrete roof deck. Dowels were not installed between the deck and curb, hence a weak connection occurred.

Table 6-1: Number of #12 screws for base case attachment of rooftop equipment

Case No	Curb Size and Equipment Type	Equipment Attachment	Fastener Factor for Each Side of Curb or Flange
1	12" x 12" Curb with Gooseneck Relief Air Hood	Hood Screwed to Curb	1.6
2	12" x 12" Gooseneck Relief Air Hood with Flange	Flange Screwed to 22 Gauge Steel Roof Deck	2.8
3	12" x 12" Gooseneck Relief Air Hood with Flange	Flange Screwed to 15/32" OSB Roof Deck	2.9
4	24" x 24" Curb with Gooseneck Relief Air Hood	Hood Screwed to Curb	4.6
5	24" x 24" Gooseneck Relief Air Hood with Flange	Flange Screwed to 22 Gauge Steel Roof Deck	8.1
6	24" x 24" Gooseneck Relief Air Hood with Flange	Flange Screwed to 15/32" OSB Roof Deck	8.2
7	24" x 24" Curb with Exhaust Fan	Fan Screwed to Curb	2.5
8	36" x 36" Curb with Exhaust Fan	Fan Screwed to Curb	3.3
9	5'-9" x 3'- 8" Curb with 2'- 8" high HVAC Unit	HVAC Unit Screwed to Curb	4.5*
10	5'-9" x 3'- 8" Curb with 2'- 8" high Relief Air Hood	Hood Screwed to Curb	35.6*

Notes to Table 6-1:

1. The loads are based on ASCE 7-05. The resistance includes equipment weight. When using ASCE 7-10, convert the 7-10 Category III / IV basic wind speed to a 7-05 basic wind speed as follows: 7-10 speed divided by the square root of (1.15 x 1.6) = 7-05 speed.

2. The Base Case for the tabulated numbers of #12 screws (or ¼ pan-head screws for flange-attachment) is a 90-mph basic wind speed, 1.15 importance factor, 30' building height, Exposure C, using a safety factor of 3. The 7-05 Base Case is equivalent to 120 mph for 7-10 Risk Category III and IV buildings.

3. For other basic wind speeds, multiply the tabulated number of #12 screws by $\left(\frac{V_D^2}{90^2}\right)$ to determine the required number of #12 screws (or ¼ pan-head screws) required for the desired basic wind speed, V_D (mph).

4. For other roof heights up to 200', multiply the tabulated number of #12 screws by (1.00 + 0.003 [h - 30]) to determine the required number of #12 screws or ¼ pan-head screws for buildings between 30' and 200'.

   Example A: 24" x 24" exhaust fan screwed to curb (table row 7), Base Case conditions (see Note 1): 2.5 screws per side; therefore, round up and specify 3 screws per side.

   Example B: 24" x 24" exhaust fan screwed to curb (table row 7), Base Case conditions, except 120 mph: 120^2 x 1 ÷ 90^2 = 1.78 x 2.5 screws per side = 4.44 screws per side; therefore, round down and specify 4 screws per side.

   Example C: 24" x 24" exhaust fan screwed to curb (table row 7), Base Case conditions, except 150' roof height: 1.00 + 0.003 (150' - 30') = 1.00 + 0.36 = 1.36 x 2.5 screws per side = 3.4 screws per side; therefore, round down and specify 3 screws per side.

* This factor only applies to the long sides. At the short sides, use the fastener spacing used at the long sides.

Figure 6-91: The gooseneck on this building remained attached to the curb, but the curb detached from the deck. Typhoon Paka (Guam, 1997)

Fan cowling attachment: Fans are frequently blown off their curbs because they are poorly attached. When fans are well attached, the cowlings frequently blow off during high winds (see Figure 6-92). Blown-off cowlings can tear roof membranes and break glazing. Unless the fan manufacturer specifically engineered the cowling attachment to resist the design wind load, cable tie-downs (see Figure 6-93) are recommended to avoid cowling blow-off where the basic wind speed is greater than 120 mph.[31] For fan cowlings less than 4 feet in diameter, ⅛-inch diameter stainless steel cables are recommended. For larger cowlings, use 3⁄16-inch diameter cables. When the basic wind speed is 165 mph or less, specify two cables.[32] Where the basic wind speed is greater than 165 mph, specify four cables. To minimize leakage potential at the anchor point, it is recommended that the cables be adequately anchored to the equipment curb (rather than anchored to the roof deck). The attachment of the curb itself also needs to be designed and specified.

To avoid corrosion-induced failure (Figure 6-105), it is recommended that exterior-mounted mechanical, electrical, and communications equipment be made of nonferrous metals, stainless steel, or steel with minimum G-90 hot-dip galvanized coating for the equipment body, stands, anchors, and fasteners. When equipment with enhanced corrosion protection is not available, the designer should advise the building owner that periodic equipment maintenance and inspection is particularly important to avoid advanced corrosion and subsequent equipment damage during a windstorm.

31 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

32 The 165-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 120 mph.

Figure 6-92: Cowlings blew off two of the three fans. Note also the loose LPS conductors and missing walkway pad (red arrow). Estimated wind speed: 140–160 mph. Hurricane Charley (Florida, 2004)

Figure 6-93: Cables were attached to prevent the cowling from blowing off. Typhoon Paka (Guam, 1997)

Ductwork: To avoid wind and wind-borne debris damage to rooftop ductwork, it is recommended that ductwork not be installed on the roof (see Figure 6-138). If ductwork is installed on the roof, it is recommended that the ducts' gauge and the method of attachment be able to resist the design wind loads.

Condenser attachment: In lieu of placing rooftop-mounted condensers on wood sleepers resting on the roof (see Figure 6-94), it is recommended that condensers be anchored to equipment stands. The attachment of the stand to the roof deck also needs to be designed to resist the design loads. In addition to anchoring the base of the condenser to the stand, two metal straps with two side-by-side #12 screws or bolts with proper end and edge distances at each strap end are recommended where the basic wind speed is greater than 120 mph (see Figure 6-95).[33]

Figure 6-94: These condensers were blown off their sleepers. Displaced condensers can rupture roof membranes and refrigerant lines. Estimated wind speed: 120 mph. Hurricane Katrina (Mississippi)

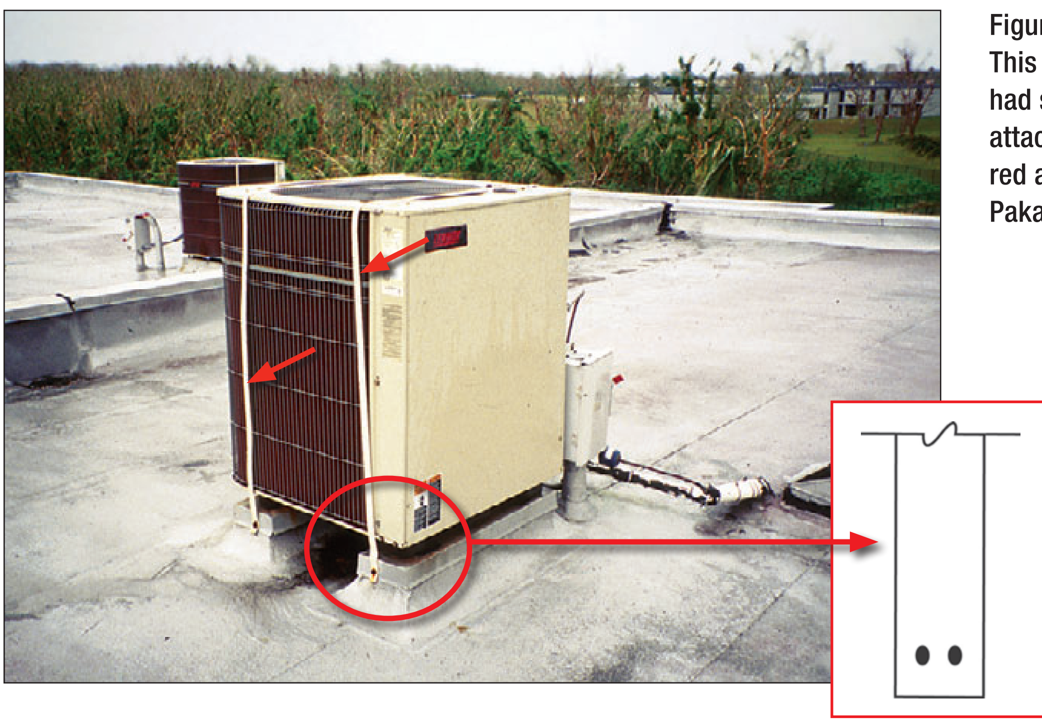


Figure 6-95: This condenser had supplemental attachment straps (see red arrows). Typhoon Paka (Guam, 1997)

33 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

Vibration isolators: If vibration isolators are used to mount equipment, only those able to resist design uplift loads should be specified and installed, or an alternative means to accommodate uplift resistance should be provided (see Figure 6-96).

Figure 6-96:
Failure of vibration isolators that provided lateral resistance but no uplift resistance caused equipment damage. A damaged vibration isolator is shown in the inset. Estimated wind speed: 120 mph. Hurricane Katrina (Mississippi, 2005)

Boiler and exhaust stack attachment: To avoid wind damage to boiler and exhaust stacks, wind loads on stacks should be calculated and guy-wires should be designed and constructed to resist the loads. Toppled stacks, as shown at the building in Figure 6-97, can allow water to enter the building at the stack penetration, damage the roof membrane, and become wind-borne debris. The designer should advise the building owner that guy-wires should be inspected annually to ensure they are taut.

Three publications pertaining to seismic restraint of equipment provide general information on fasteners and edge distances:

- FEMA 412, *Installing Seismic Restraints for Mechanical Equipment* (2002)
- FEMA 413, *Installing Seismic Restraints for Electrical Equipment* (2004b)
- FEMA 414, *Installing Seismic Restraints for Duct and Pipe* (2004a)

Access panel attachment: Equipment access panels frequently blow off (see Figure 6-98). Unless the equipment manufacturer specifically engineered the panel attachment to resist the design wind load, job-site modifications, such as attaching hasps and locking devices like carabiners, are recommended. The modification details need to be customized. Detailed design may be needed after the equipment has been delivered to the job site. Modification details should be approved by the equipment manufacturer.

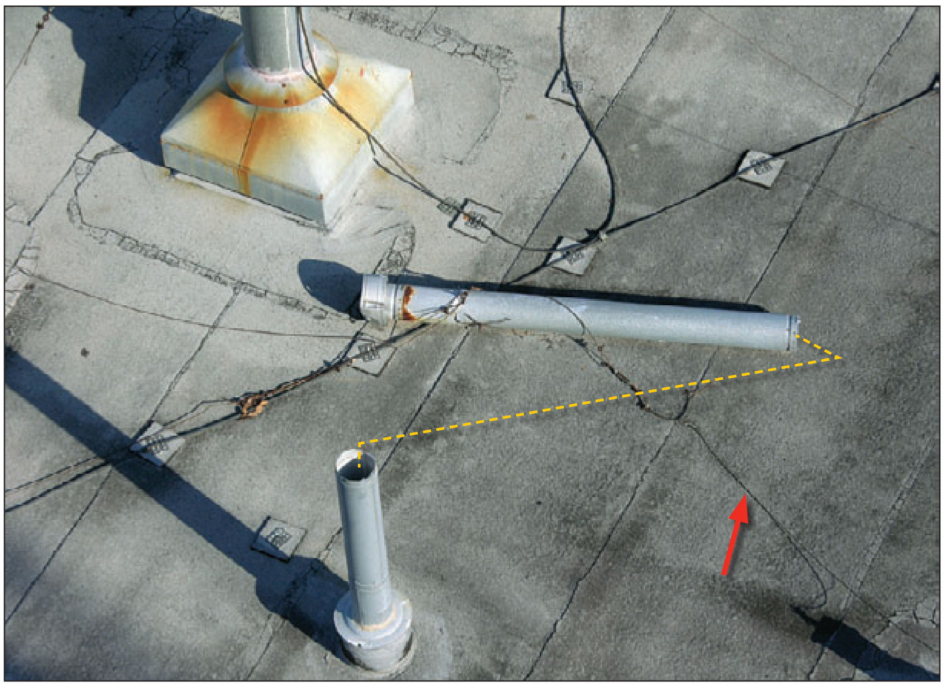


Figure 6-97:
Guyed flue blew over (red arrow indicates one of the guys). Estimated wind speed: 92 mph. Hurricane Ike (Texas, 2008)

Figure 6-98:
The school shown in Figure 6-65 also had an access panel blow off. Blown-off panels can puncture roof membranes, break glazing, and cause injury. Estimated wind speed: 85–95 mph. Hurricane Ivan (Florida, 2004)

Natural gas and condensate drain lines: Natural gas lines and condensate drain lines serving rooftop HVAC units are seldom anchored to resist wind loads. Gas line rupture can be due to lack of line anchorage or due to HVAC unit blow-off (see Figures 6-57 and 6-99). Where the basic wind speed is greater than 120 mph,[34] it is recommended that gas line supports be designed and constructed to resist the design wind load (see Figure 6-100).

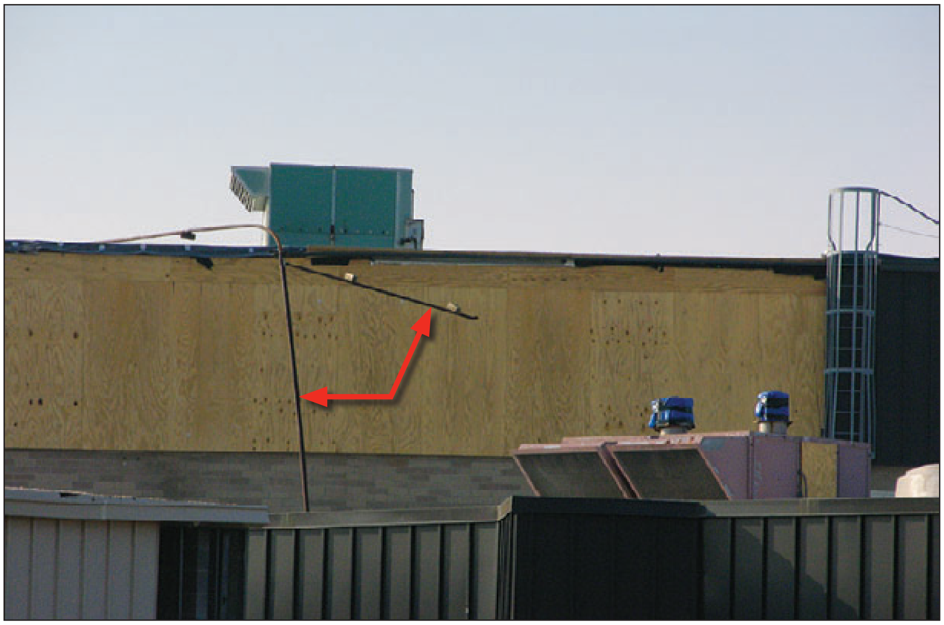


Figure 6-99: The school shown in Figures 6-65 and 6-98 also experienced gas line rupture (shown by the lines dangling over the side of the building). Estimated wind speed: 85–95 mph. Hurricane Ivan (Florida, 2004)

Figure 6-100: At a periodic gas line support on this roof, a steel angle was welded to a pipe that was anchored to the roof deck. A strap looped over the gas line and was bolted to the support angle. Such a connection provides resistance to lateral and uplift loads.

34 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

Although blow-off of condensate drain lines is not as potentially catastrophic as rupture of gas lines, blown off condensate drain lines can puncture roof membranes, break glazing, and cause injury (see Figure 6-101). Where the basic wind speed is greater than 120 mph,[35] it is recommended that condensate drain line supports be designed and constructed to resist the design wind load.

Figure 6-101: These two condensate drain lines detached from their HVAC units. They had not been anchored to the roof. Estimated wind speed: 125 mph. Hurricane Katrina (Mississippi, 2005)

Equipment screens: Screens around rooftop equipment are frequently blown away (see Figure 6-102). Screens should be designed to resist the wind load derived from ASCE 7. Since the effect of screens on equipment wind loads is unknown, the equipment attachment behind the screens should be designed to resist the design load.

Water Infiltration

During high winds, wind-driven rain can be driven through air intakes and exhausts unless special measures are taken. Louvers should be designed and constructed to prevent leakage between the louver and wall. The louver itself should be designed to avoid water being driven past the louver. However, it is difficult to prevent infiltration during very high winds. Designing sumps with drains that will intercept water driving past louvers or air intakes should be considered. ASHRAE 62.1 provides some information on rain and snow intrusion. The *Standard 62.1 User's Manual* (2007a) provides additional information, including examples and illustrations of various designs.

35 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

Figure 6-102: Equipment screen panels can puncture roof membranes, break glazing, and cause injury. Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida, 2004)

6.3.4.2 Nonstructural Systems and Mechanical Equipment in Hurricane-Prone Regions

Mechanical Penthouses: By placing equipment in mechanical penthouses rather than leaving them exposed on the roof, equipment can be shielded from high-wind loads and wind-borne debris (see Figure 6-103). Although screens (such as shown in Figure 6-102) could be designed and constructed to protect equipment from horizontally flying debris, they are not effective in protecting equipment from missiles that have an angular trajectory. It is therefore recommended that mechanical equipment be placed inside mechanical penthouses. The penthouse itself should be designed and constructed in accordance with the recommendations given in Sections 6.3.2.2, 6.3.3.5, and 6.3.3.7.

If rooftop ductwork is exposed on the roof, and if there are flexible connectors between the ducts and fans, the connectors may be punctured by wind-borne debris. If equipment is not protected by a penthouse, the following is recommended:

- Because of their small size, the potential for a flexible connector to be punctured by wind-borne debris is typically very low. However, if site-specific conditions present an unusually high potential for debris damage, it is recommended that the flexible connectors be protected by equipment screens or a custom-designed shield.

As part of annual roof inspections prior to hurricane season, it is recommended that all flexible connectors be inspected. Those found to be in a weathered condition (e.g., cracked, torn, or embrittled) should be immediately replaced.

Figure 6-103: This exhaust fan was impacted by wind-borne debris. Although it is often impractical to place all equipment such as fans in penthouses, doing so to the extent possible avoids debris damage. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

Roof drainage: Roof drains and scuppers have the potential to be blocked by leaves, tree limbs, and other wind-borne debris during a hurricane (see Figure 6-104). If primary and overflow drains/scuppers become blocked, development of deep ponding water may inundate base flashings and cause leakage problems or lead to roof collapse. To avoid problems with blocked drains and scuppers, the following are recommended:

- **Scuppers –** Only a relatively small scupper is needed to drain a large roof area, provided the scupper opening is not blocked by debris. However, since small openings are more easily blocked than larger openings, it is recommended that scupper openings be much larger than normal. It is recommended that scupper openings be a minimum of 24 inches wide and 16 inches high. In addition, it is recommended that the distance between scuppers be such that, in the event a scupper becomes blocked, the adjacent scuppers have sufficient capacity to drain the roof.

> As part of pre-storm preparations, drains, scuppers, and gutters should be cleaned of debris in order to maximize their effectiveness in draining the roof and minimize the potential for their blockage during a hurricane (see Figure 6-32).

- **Roof drains –** Avoiding blockage of drains is more problematic than avoiding blockage of scuppers. Drain lines need to be protected by domes to prevent debris from flowing into the lines and blocking them. For domes to be effective in protecting drain lines from blockage, the dome openings must be relatively small. To provide overflow protection, it is recommended that overflow scuppers be provided. Where drainage patterns necessitate that overflow protection be provided by overflow drains (rather than, or in addition to, overflow scuppers), it is recommended that additional overflow drains be installed. By doing so, if both a main drain and its nearby overflow drain become blocked, the additional overflow drain in the vicinity can provide drainage and avoid roof collapse.

Figure 6-104:
Leaf debris and ponding near a scupper (red and blue arrows). The yellow arrow indicates a piece of coping that blew off an upper roof shown in Figure 6-72. Estimated wind speed: 92 mph. Hurricane Ike (Texas, 2008)

6.3.4.3 Exterior-Mounted Electrical and Communications Equipment

Damage to exterior-mounted electrical equipment is infrequent, mostly because of its small size (e.g., disconnect switches). Exceptions include communication towers, surveillance cameras, electrical service masts, satellite dishes, and LPSs. The damage is typically caused by inadequate mounting as a result of failure to perform wind load calculations and anchorage design. Damage is also sometimes caused by corrosion (see Figure 6-105 and text box in Section 6.3.4.1 regarding corrosion).

Figure 6-105: Collapsed light fixtures caused by severe corrosion (see inset). Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida, 2004)

Communication towers and poles: NFPA 70 provides guidance for determining wind loads on power distribution and transmission poles and towers. AASHTO LTS-4-5 provides guidance for determining wind loads on light fixture poles (standards).

Both ASCE 7 and ANSI/TIA-222-G contain wind load provisions for communication towers (structures). The IBC allows the use of either approach. The ASCE wind load provisions are generally consistent with those contained in ANSI/TIA-222-G. ASCE 7, however, contains provisions for dynamically sensitive towers that are not present in the ANSI/TIA standard. ANSI/TIA classifies towers according to their use (Class I, Class II, and Class III). This manual recommends that towers (including antennae) that are mounted on, located near, or serve schools be designed as Class III structures.

Collapse of both large and small communication towers is quite common during high-wind events (see Figure 6-106). These failures often result in complete loss of communication capabilities. In addition to the disruption of communications, collapsed towers can puncture roof membranes and allow water leakage into the school, unless the roof system incorporated a secondary membrane (as discussed in Section 6.3.3.7). At the tower shown in Figure 6-106 the anchor bolts were pulled out of the deck, which resulted in a progressive peeling of the fully adhered single-ply roof membrane. Tower collapse can also injure or kill people.

Figure 6-106: The collapse of the antenna tower at this school caused progressive peeling of the roof membrane. Also note that the exhaust fan blew off the curb, but the high parapet kept it from blowing off the roof. Hurricane Andrew (Florida, 1992)

See Sections 6.3.1.1 and 6.3.1.5 regarding site considerations for light fixture poles, power poles, and electrical and communications towers.

Electrical service masts: Service mast failure is typically caused by collapse of overhead power lines, which can be avoided by using underground service. Where overhead service is provided, it is recommended that the service mast not penetrate the roof. Otherwise, a downed service line could pull on the mast and rupture the roof membrane.

Satellite dishes: For the satellite dish shown in Figure 6-107, the dish mast was anchored to a large metal pan that rested on the roof membrane. CMU was placed on the pan to provide overturning resistance. This anchorage method should only be used where calculations demonstrate that it provides sufficient resistance. In this case, the wind approached the satellite dish in such a way that it experienced very little wind pressure. In hurricane-prone regions, use of this anchorage method is not recommended (see Figure 6-108).

Lightning protection systems (LPS): For attachment of building LPS located where the basic wind speed is in excess of 120 mph,[36] see the following section on attaching LPS in hurricane-prone regions.

36 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

Figure 6-107: Common anchoring method for satellite dish. Estimated wind speed: 85–95 mph. Hurricane Ivan (Florida, 2004)

Figure 6-108: A satellite dish anchored similarly to that shown in Figure 6-107 was blown off this five-story building. Estimated wind speed: 140–160 mph. Hurricane Charley (Florida, 2004)

6.3.4.4 Lightning Protection Systems in Hurricane-Prone Regions

LPSs frequently become disconnected from rooftops during hurricanes. Displaced LPS components can puncture and tear roof coverings, thus allowing water to leak into buildings (see Figures 6-109 and 6-110). Prolonged and repeated slashing of the roof membrane by loose conductors ("cables") and puncturing by air terminals ("lightning rods") can result in lifting and peeling of the membrane. Also, when displaced, the LPS is no longer capable of providing lightning protection in the vicinity of the displaced conductors and air terminals.

Figure 6-109:
An air terminal (red arrow) debonded from the roof. Even though the school had a tough membrane (modified bitumen), the displaced air terminal punctured the membrane in two locations (blue arrows). Hurricane Charley (Florida, 2004)

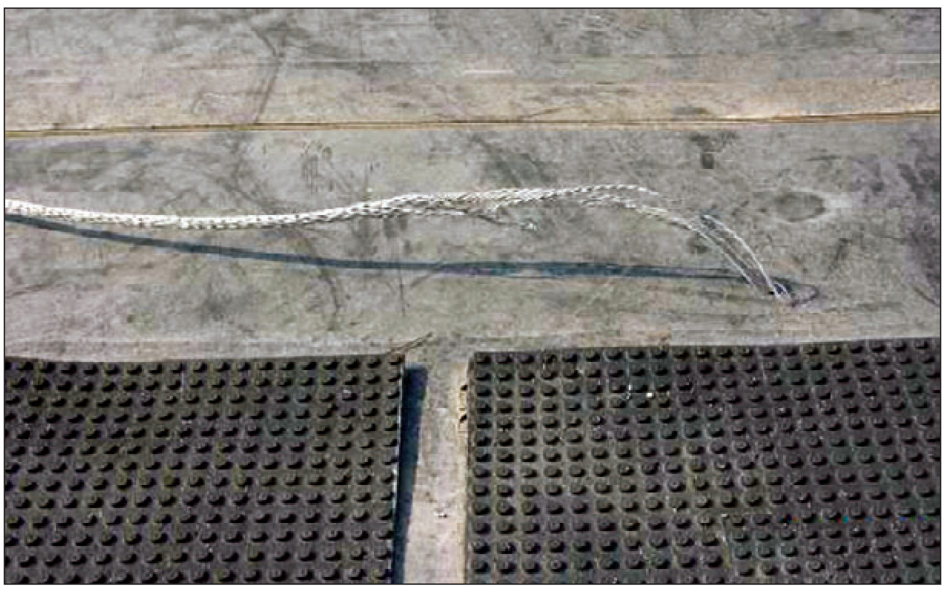


Figure 6-110:
View of an end of a conductor that became disconnected. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

Lightning protection standards such as NFPA 780 and UL 96A provide inadequate guidance for attaching LPSs to rooftops in hurricane-prone regions, as are those recommendations typically provided by LPS and roofing material manufacturers. LPS conductors are typically attached to the roof at 3-foot intervals. The conductors are flexible, and when they are exposed to high winds, the conductors exert dynamic loads on the conductor connectors ("clips"). Guidance for calculating the dynamic loads does not exist. LPS conductor connectors typically have prongs to anchor the conductor. When the connector is well-attached to the roof surface, during high winds the conductor frequently bends back the malleable connector prongs (see Figure 6-111). Conductor connectors have also debonded from roof surfaces during high winds. Based on observations after Hurricane Ike and other hurricanes, it is apparent that pronged conductor connectors typically have not provided reliable attachment.

Figure 6-111: This conductor connector was adhered to the coping. The conductor deformed the connector prongs under wind pressure, and pulled away from the connector. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

To enhance the wind performance of LPS, the following are recommended:

Parapet attachment: When the parapet is 12 inches high or greater, it is recommended that the air terminal base plates and conductor connectors be mechanically attached with #12 screws that have minimum 1¼-inch embedment into the inside face of the parapet nailer and be properly sealed for watertight protection. Instead of conductor connectors that have prongs, it is recommended that mechanically attached looped connectors be installed (see Figure 6-112).

Figure 6-112: This conductor was attached to the coping with a looped connector. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

Attachment to built-up, modified bitumen, and single-ply membranes: For built-up and modified bitumen membranes, attach the air terminal base plates with asphalt roof cement. For single-ply membranes, attach the air terminal base plates with pourable sealer (of the type recommended by the membrane manufacturer).

In lieu of attaching conductors with conductor connectors, it is recommended that conductors be attached with strips of membrane installed by the roofing contractor. For built-up and modified bitumen membranes, use strips of modified bitumen cap sheet, approximately 9 inches wide at a minimum. If strips are torch-applied, avoid overheating the conductors. For single-ply membranes, use self-adhering flashing strips, approximately 9 inches wide at a minimum. Start the strips approximately 3 inches from either side of the air terminal base plates. Use strips that are approximately 3 feet long, separated by a gap of approximately 3 inches (see Figures 6-113 and 6-114).

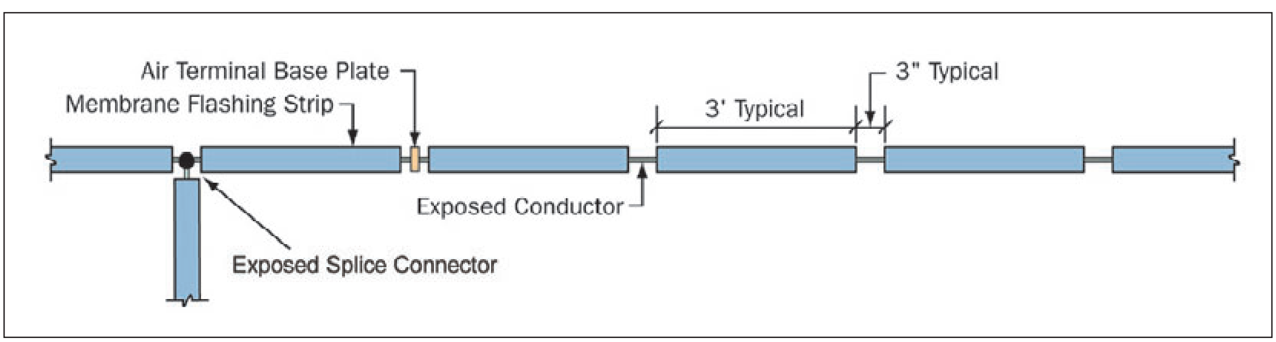


Figure 6-113: Plan showing conductor attachment

Figure 6-114: Use of intermittent membrane flashing strips to secure an LPS conductor, as illustrated in Figure 6-113

PHOTO COURTESY OF: MACGREGOR ASSOCIATES ARCHITECTS.

As an option to securing the conductors with stripping plies, conductor connectors that do not rely on prongs could be used (such as the one shown in Figure 6-115). However, the magnitude of the dynamic loads induced by the conductor is unknown, and there is a lack of data on the resistance provided by adhesively attached connectors. For this reason, attachment with stripping plies is the preferred option, because the plies shield the conductor from the wind. If adhesive-applied conductor connectors are used, it is recommended that they be spaced more closely than the 3-foot spacing required by NFPA 780 and UL 96A. Depending on wind loads, a spacing of 6 to 12 inches on center may be needed in the corner regions of the roof, with a spacing of 12 to 18 inches on center at roof perimeters (see ASCE 7 for the size of corner regions).

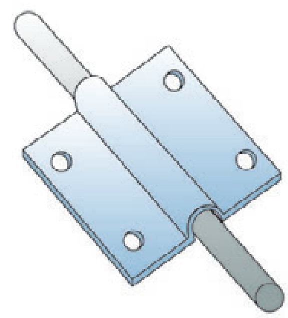


Figure 6-115: Adhesively attached conductor connector that does not use prongs

Mechanically attached single-ply membranes: It is recommended that conductors be placed parallel to, and within 8 inches of, membrane fastener rows. Where the conductor falls between or is perpendicular to membrane fastener rows, install an additional row of membrane fasteners where the conductor will be located, and install a membrane cover-strip over the membrane fasteners. Place the conductor over the cover-strip and secure the conductor as recommended above.

By following the above recommendations, additional rows of membrane fasteners (beyond those needed to attach the membrane) may be needed to accommodate the layout of the conductors. The additional membrane fasteners and cover-strip should be coordinated with, and installed by, the roofing contractor.

It is recommended that the building designer advise the building owner to have the LPS inspected each spring, to verify that connectors are still attached to the roof surface, that they still engage the conductors, and that the splice connectors are still secure. Inspections are also recommended after high-wind events.

Standing seam metal roofs: It is recommended that pre-manufactured, mechanically attached clips that are commonly used to attach various items to roof panels be used. After anchoring the clips to the panel ribs, the air terminal base plates and conductor connectors are anchored to the panel clips. In lieu of conductor connectors that have prongs, it is recommended that mechanically attached looped connectors be installed (see Figure 6-112).

Conductor splice connectors: In lieu of pronged splice connectors (see Figure 6-116), bolted splice connectors are recommended because they provide a more reliable connection (see Figure 6-117). It is recommended that strips of flashing membrane (as recommended above) be placed approximately 3 inches from either side of the splice connector to minimize conductor movement and to avoid the possibility of the conductors becoming disconnected. To allow for observation during maintenance inspections, do not cover the connectors.

Figure 6-116: If conductors detach from the roof, they are likely to pull out from pronged splice connectors. Estimated wind speed: 90–100 mph. Hurricane Charley (Florida, 2004)

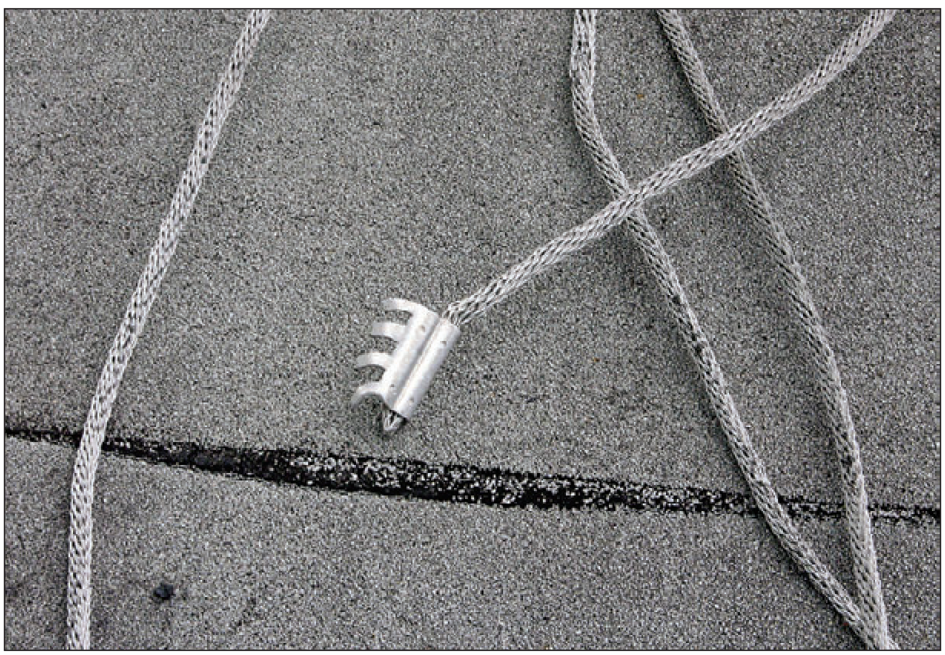


Figure 6-117: Bolted splice connectors are recommended to prevent free ends of connectors from being whipped around by wind. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

6.3.5 Municipal Utilities In Hurricane-Prone Regions

Hurricanes typically disrupt municipal electrical service, and often they disrupt telephone (both cellular and land-line), water, and sewer services. These disruptions may last from several days to several weeks. Electrical power disruptions can be caused by damage to power generation stations and by damaged lines, such as major transmission lines and secondary feeders. Water disruptions can be caused by damage to water treatment or well facilities, lack of power for pumps or treatment facilities, or by broken water lines caused by uprooted trees. Sewer disruptions can be caused by damage to treatment facilities, lack of power for treatment facilities or lift stations, or broken sewer lines. Phone disruptions can be caused by damage at switching facilities and collapse of towers.

When a portion of a school is designed to function as a safe room, additional design criteria for backup or emergency power for the safe room portion of the school must meet additional performance criteria set forth in FEMA 361. In addition to backup power criteria, the safe room guidance identifies lighting, sewer, and water services.

For schools that will be used as hurricane evacuation shelters, provisions should be made to accommodate disruption of municipal utilities, as discussed in 6.3.5.1, 6.3.5.2, and 6.3.5.3.

For schools that will be used as recovery centers after a hurricane, it is recommended that the schools be equipped with an emergency generator or have pre-hurricane arrangements for delivery of a portable generator to the school prior to the recovery center becoming operational (see Figure 6-118). (Note: It could take a few or several days for a portable generator to be delivered.) If a portable generator rather than a permanent on-site generator will be relied upon for power, it is recommended that an exterior box for single pole cable cam locking connectors be provided so that the portable generator can be quickly connected. The generator should be capable of providing power to items listed in Section 6.3.5.1. To provide for back-up water and sewer service, either the provisions discussed in 6.3.5.2 and 6.3.5.3, or pre-hurricane arrangements for delivery of water and portable toilets to the school prior to the recovery center becoming operational, are recommended.

Figure 6-118: In lieu of permanent on-site emergency generators, portable generators can be an economical way to provide electrical power to schools used as hurricane recovery centers. Estimated wind speed: 108 mph. Hurricane Ike (Texas, 2008)

For schools that will not be used as hurricane evacuation shelters or recovery centers, in lieu of spending money to incorporate provisions to accommodate disruption of municipal utilities, school re-opening could be delayed until municipal utilities are operational. (Note: In many instances, schools can't re-open for a couple of weeks after a hurricane because of various issues [such as debris removal from roads and school grounds] unrelated to utilities.)

6.3.5.1 Electrical Power

It is recommended that schools that will be used as hurricane evacuation shelters be provided with an emergency generator to supply power for lighting, exit signs, fire alarm system, fire sprinkler pump, public address system, and for mechanical ventilation. The emergency generator should be rated for prime power (continuous operation).

Generators should be placed inside wind-borne debris resistant buildings (see recommendations in Sections 6.3.2.2, 6.3.3.5, and 6.3.3.7) so that they are not susceptible to damage from debris or tree fall. Locating generators outdoors or inside weak enclosures (see Figure 6-119) is not recommended.

Figure 6-119: The tree shown by the red line nearly fell on the emergency generator (red arrow). Estimated wind speed: 110 mph. Hurricane Ike (Texas, 2008)

It is recommended that wall louvers for generators be capable of resisting the test Missile E load specified in ASTM E 1996. Alternatively, wall louvers can be protected with a debris-resistant screen wall so that wind-borne debris is unable to penetrate the louvers and damage the generators. If a screen wall is used, it should be designed to allow adequate air flow to the generator in order to avoid overheating the generator.

Generators fired by natural gas are available. Use of natural gas alleviates various potential problems associated with on-site storage of diesel fuel (such as adequate quantity of fuel for prolonged outages). However, if the natural gas supply is shut down by the gas supplier, the school will be left without power.

It is recommended that sufficient on-site fuel storage be provided to allow the facility's emergency generator to operate at full capacity for a minimum of 72 hours (3 days). It is recommended that fuel storage tanks, piping, and pumps be placed inside wind-borne debris resistant buildings, or underground. If the site is susceptible to flooding, refer to Chapter 5 recommendations.

6.3.5.2 Water Service

It is recommended that schools that will be used as hurricane evacuation shelters be provided with an independent water supply via a well or on-site water storage for drinking water, fire sprinklers (if they exist), and water-operated toilets. If water is needed for cooling towers, the independent water supply should be sized to accommodate the system.

It is recommended that pumps for wells or on-site storage be connected to an emergency power circuit, that a valve be provided on the municipal service line, and that on-site water treatment capability be provided where appropriate.

6.3.5.3 Sewer Service

It is recommended that schools that will be used as hurricane evacuation shelters be provided with portable chemical toilets or an alternative means of waste disposal, such as a temporary storage tank that can be pumped out by a local contractor. It is also recommended that back-flow preventors be provided in the sewage discharge lines.

6.3.6 Post-Design Considerations in Hurricane-Prone Regions

In addition to adequate design, proper attention must be given to construction, post-occupancy inspections, and maintenance.

6.3.6.1 Construction Contract Administration

It is important for school districts in hurricane-prone regions to obtain the services of a professional contractor who will execute the work described in the contract documents in a diligent and technically proficient manner. The frequency of field observations and extent of special inspections and testing should be greater than those employed on schools that are not in hurricane-prone regions. The frequency of field observations and extent of special inspections and testing should be even greater for schools that will be used as hurricane evacuation shelters.

6.3.6.2 Periodic Inspections, Maintenance, and Repair

The recommendations given in Section 6.3.1.4 for post-occupancy and post-storm inspections, maintenance, and repair are crucial for schools in hurricane-prone regions. Failure of a building component that was not maintained properly, repaired, or replaced, can present a considerable risk of injury or death to occupants if the school is used as a hurricane evacuation shelter, and the continued operation of the facility can be jeopardized.

> Refer to the two text boxes in Sections 6.3.4.2 that addresses inspection of flexible connectors at ducts and inspection of drains, scuppers, and gutters. Also refer to the text box in Section 6.3.4.4 that addresses inspection of lightning protection systems.

6.4 Remedial Work on Existing Facilities

Many existing schools need to strengthen their structural or building envelope components. The reasons for this are the deterioration that has occurred over time, or inadequate facility strength to resist current design level winds. It is recommended that school districts have a vulnerability assessment performed by a qualified architectural and engineering team. A vulnerability assessment should be performed for all facilities older than 5 years. An assessment is recommended for all facilities located in areas where the basic wind speed is greater than 120 mph[37] (even if the facility is younger than 5 years—see Figure 6-120). It is particularly important to perform vulnerability assessments on schools located in hurricane-prone and tornado-prone regions.

Figure 6-120:
The roof and a portion of the EIFS on this 5-year-old building blew off. Water leaked into the floor below. The floor was taken out of service for more than a month. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

Components that typically make buildings constructed before the early 1990s vulnerable to high winds are weak non-load-bearing masonry walls, poorly connected precast concrete panels, long-span roof structures with limited uplift resistance, inadequately connected roof decks, weak glass curtain walls, building envelope, and exterior-mounted equipment. Although the technical solutions to these problems are not difficult, the cost of the remedial work is typically quite high. If funds are not available for strengthening or replacement, it is important to minimize the risk of injury and death by evacuating areas adjacent to

37 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

weak non-load-bearing walls, weak glass curtain walls, and areas below long-span roof structures when winds above 60 mph are forecast.

As a result of building code changes and heightened awareness, some of the common building vulnerabilities have generally been eliminated for facilities constructed in the mid-1990s or later. Components that typically remain vulnerable to high winds are the building envelope and exterior-mounted mechanical, electrical, and communications equipment. Many failures can be averted by identifying weaknesses and correcting them.

By performing a vulnerability assessment, items that need to be strengthened or replaced can be identified and prioritized. A proactive approach in mitigating weaknesses can save significant sums of money and decrease disruption or total breakdown in school operations after a storm. For example, a vulnerability assessment on a building such as that shown in Figure 6-120 may identify weakness of the roof membrane and/or EIFS. Replacing weak components before a storm is much cheaper than replacing them and repairing consequential damages after a storm, and proactive work avoids the loss of use while repairs are made.

Before beginning remedial work, it is necessary to understand all significant aspects of the vulnerability of a school with respect to wind and wind-driven rain. If funds are not available to correct all identified deficiencies, the work should be systematically prioritized so that the items of greatest need are corrected first. Mitigation efforts can be very ineffective if they do not address all items that are likely to fail.

If budget constraints prohibit timely evaluation of all schools in the district, then facility evaluation should be prioritized, commensurate with district's needs and the perceived vulnerabilities of the facilities. For example, schools that will be used as hurricane evacuation shelters, recovery centers after a hurricane, and facilities constructed before the early 1990s would normally be evaluated first. Upon completion of the evaluations of the district's facilities, the order in which remedial work will be scheduled should be prioritized.

For those schools that will be used as hurricane evacuation shelters or as recovery centers after a hurricane, the vulnerability assessment should also evaluate the facility's capability of coping with loss of municipal utilities (i.e., electrical power, water, sewer, and communications).

A comprehensive guide for performing a vulnerability assessment and for remedial work on existing facilities is beyond the scope of this manual. However, the checklist in Section 6.6 provides a guide for vulnerability assessment, and the remainder of this Section provides examples of mitigation measures that are often applicable.

6.4.1 Structural Systems

As discussed in Section 6.1.4.1, roof decks on many facilities designed prior to the 1982 edition of the SBC and UBC and the 1987 edition of the NBC are very susceptible to failure. Poorly attached decks that are not upgraded are susceptible to blow-off, as shown in Figure 6-121. Decks constructed of cementitious wood-fiber, gypsum, and lightweight insulating concrete over form boards were commonly used on schools built in the 1950s and 1960s. In that era, these types of decks, as well as precast concrete decks, typically had very limited uplift resistance due to weak connections to the support structure. Steel deck attachment is frequently not adequate because of an inadequate number of welds, or welds of poor quality. Older buildings with overhangs are particularly susceptible to blow-off, as shown in Figure 6-121, because older codes provided inadequate uplift criteria.

Figure 6-121
The cementitious wood-fiber deck panels blew off of much of the overhang at this school. Deck panel failure resulted in lifting and peeling of the roof system over a large area, exposure of the decking in the area shown by the blue arrows, and extensive interior water infiltration. Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida, 2004)

PHOTO COURTESY OF RICOWI, INC. PHOTO #:PD02-047 4-08-4. PHOTOGRAPHER: PHIL DREGGER, TECHNICAL ROOF SERVICES, INC.

A vulnerability assessment of the roof deck should include evaluating the existing deck attachment, spot checking the structural integrity of the deck (including the underside, if possible), and evaluating the integrity of the beams/joists. If the deck attachment is significantly overstressed under current design wind conditions or the deck integrity is compromised, the deck should be replaced or strengthened as needed. The evaluation should be conducted by an investigator experienced with the type of deck used on the building.

The vulnerability assessment should also include evaluating the structural integrity of canopies, for as shown in Figure 6-41, these elements often lack sufficient wind resistance.

If a low-slope roof is converted to a steep-slope roof, the new support structure should be engineered and constructed to resist the wind loads and avoid the kind of damage shown in Figure 6-122.

Figure 6-122: The steel truss superstructure installed on this school as part of a steep-slope conversion blew away because of inadequate attachment. Hurricane Marilyn (U.S. Virgin Islands, 1995)

6.4.2 Building Envelope

Because of the lack of field diagnostic equipment and test methods, it is quite difficult to accurately assess the wind and wind-driven rain vulnerability of the building envelope and rooftop equipment. Review of existing drawings (if available) often times reveal vulnerabilities. However, it is frequently necessary to perform selective destructive observation as part of the assessment. A successful assessment is dependent upon the school district budgeting sufficient funds for the assessment and upon the expertise, experience, and judgment of design professionals performing the assessment. The following recommendations apply to building envelope components of existing schools.

6.4.2.1 Windows and Skylights

Windows in older facilities may possess inadequate resistance to wind pressure. Window failures are typically caused by wind-borne debris, however, glazing or window frames may fail as a result of wind pressure (see Figure 6-123). Failure can be caused by inadequate resistance of the glazing, inadequate anchorage of the glazing to the frame, failure of the frame itself, or inadequate attachment of the frame to the wall. For older windows that are too weak to resist the current design pressures, window assembly replacement is recommended.

Figure 6-123: Wind pressure caused the window frames on the upper floors to fail (red arrow). Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

Some older window assemblies have sufficient strength to resist the design pressure, but are inadequate to resist wind-driven rain. If the lack of water resistance is due to worn glazing gaskets or sealants, replacing the gaskets or sealant may be viable. In other situations, replacing the existing assemblies with new, higher-performance assemblies may be necessary. On-site testing in accordance with ASTM E 1105 can be used to evaluate wind-driven rain resistance of suspect windows (see Figure 6-124). (Note: Shutters placed over windows to provide wind-borne debris protection should not be relied upon to protect against wind-driven rain. If existing windows are susceptible to debris and leakage, the windows should be replaced with new assemblies.)

Figure 6-124: On-site water-spray testing in accordance with ASTM E 1105 can be used to evaluate wind-driven rain resistance. Older window assemblies such as the ones at this school are often quite susceptible to leakage. Estimated wind speed: 125 mph. Hurricane Katrina (Mississippi, 2005)

It is recommended that all non-impact-resistant, exterior glazing located in hurricane-prone regions (with a basic wind speed of 135 mph or greater)[38] be replaced with impact-resistant glazing or be protected with shutters, as discussed in Section 6.3.3.3. Shutters are typically a more economical approach for existing facilities. There are a variety of shutter types, all illustrated by Figures 6-125 to 6-128. Accordion shutters are permanently attached to the wall (Figure 6-125). When a hurricane is forecast, the shutters are pulled together and latched into place. Panel shutters (Figures 6-126 and 6-127) are made of metal or polycarbonate. When a hurricane is forecast, the shutters are taken from storage and inserted into metal tracks that are permanently mounted to the wall above and below the window frame as shown in Figure 6-126 (or fastened to the building as shown in Figure 6-127). The panels are locked into the frame with wing nuts or clips. Track designs that have permanently mounted studs for the nuts have been shown to be more reliable than track designs using studs that slide into the track. A disadvantage of panel shutters is the need for storage space. Roll-down shutters (Figure 6-128) can be motorized or pulled down manually. Motorized shutters are available with toggles that allow the shutter to be manually raised. The advantage of being able to open the shutter without electrical power is that if water leaked into the building and if the door or window protected by the shutter is operable, the shutter can be manually raised in order to facilitate venting (drying of the interior).

38 The 135-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 100 mph.

Figure 6-125:
This school has accordion shutters. Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida, 2004)

Figure 6-126:
A metal panel shutter. Hurricane Georges (Puerto Rico, 1998)

Figure 6-127: Polycarbonate shutters were temporary screwed to the doors and wall adjacent to the window opening. An advantage of polycarbonate is its translucence, which allows daylight to enter the building without removing the shutters. Hurricane Francis (Florida, 2004)

Figure 6-128: This school has roll-down shutters. The toggle in the red circle allows the shutter to be manually raised. Estimated wind speed: 130–140 mph. Hurricane Charley (Florida, 2004)

Deploying accordion or panel shutters a few stories above grade is expensive. Although motorized shutters have greater initial cost, their operational cost should be lower. Other options for providing missile protection on upper levels include replacing the existing assemblies with laminated glass assemblies, or installing permanent impact resistant screens. Engineered films are also available for application to the interior of the glass. The film needs to be anchored to the frame, and the frame needs to be adequately anchored to the wall. The film degrades over time and requires replacement (approximately every decade). Use of laminated glass or shutters/screens is recommended in lieu of engineered films.

6.4.2.2 Non-Load-Bearing Walls, Wall Coverings, and Soffits

Non-load-bearing walls, wall coverings, and soffits on existing schools should be carefully examined and evaluated for wind and wind-driven rain resistance.

If the parapet is constructed of masonry, it is recommended that its wind resistance be evaluated and strengthened if found to be inadequate. The masonry parapet shown in Figure 6-129 fell onto the roof. Had it fallen in the other direction, it would have blocked the entry and would have had the potential to cause injury.

To identify weak EIFS systems so that corrective action can be taken to avoid the type of damage shown in Figures 6-61 and 6-62, on-site testing in accordance with ASTM E 2359 can be conducted. (Note: This test method is not capable of evaluating the wind resistance of the wall framing.)

Figure 6-129: Collapsed unreinforced masonry parapet. Greensburg Tornado (Kansas, 2007)

6.4.2.3 Roof Coverings

On-site testing in accordance with ASTM E 907 can be used to evaluate the uplift resistance of roof systems that have fully adhered membranes (see Figure 6-130). (Note: This test method is not capable of evaluating the uplift resistance of the roof deck.)

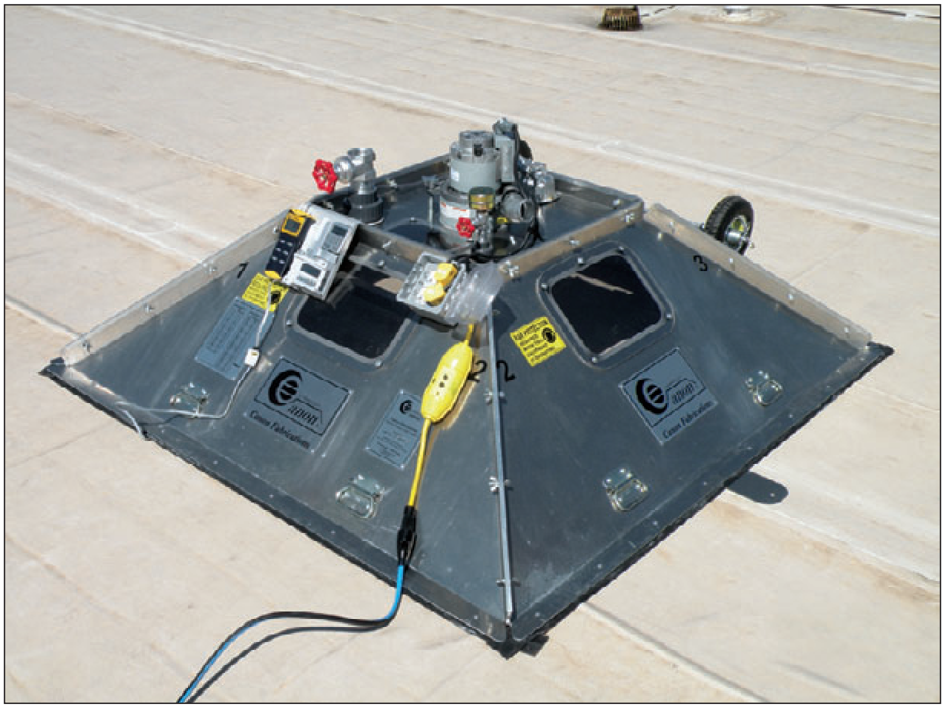


Figure 6-130: View of a 5-foot by 5-foot negative pressure chamber used to evaluate roof system uplift resistance.

For roofs with weak metal edge flashing or coping attachment, face-attachment of the edge flashing/coping (as shown in Figure 6-73) is a cost-effective approach to greatly improve the wind-resistance of the roof system. To improve the wind resistance of weak gutters, a cost-effective approach is to install straps as shown in Figure 6-77. Alternatively, if the gutter bracket attachment is sufficient to resist rotational force (as discussed in Section 6.3.3.6), but the gutter is not anchored to the brackets, fasteners can be installed to anchor the gutter to the bracket as shown in Figure 6-76.

The vulnerability assessment of roofs ballasted with aggregate, pavers, or cementitious-coated insulation boards, should determine whether the ballast complies with ANSI/SPRI RP-4. Corrective action is recommended for non-compliant, roof coverings. It is recommended that roof coverings with aggregate surfacing, lightweight pavers, or cementitious-coated insulation boards on buildings located in hurricane-prone regions be replaced to avoid blow-off (see Figures 6-8, 6-13, 6-23, and 6-53).

When planning the replacement of a roof covering, it is recommended that all existing roof covering be removed down to the deck rather than simply re-covering the roof. Tearing off the covering provides an opportunity to evaluate the structural integrity of the deck and correct deck attachment and other problems. For example, if a roof deck was deteriorated due to roof leakage (see Figure 6-131), the deterioration would likely not be identified if the roof was simply re-covered. By tearing off down to the deck, deteriorated decking like that shown in Figure 6-131 can be found and replaced. In addition, it is recommended that the attachment of the wood nailers at the top of parapets and roof edges be evaluated and strengthened where needed, to avoid blow-off and progressive lifting and peeling of the new roof membrane (see Figure 6-132).

Figure 6-131:
The built-up roof on this school was blown off after a few of the rotted wood planks detached from the joists. Estimated wind speed: 120 mph. Hurricane Katrina (Mississippi, 2005)

Figure 6-132: The nailer (red arrow) blew off an upper roof and landed on the roof below. The nailer was anchored to a brick wall. Some of the anchors pulled out of the brick, and some of the bricks blew away with the nailer. Estimated wind speed: 105–115 mph. Hurricane Ivan (Florida), 2004

If the roof has a parapet, it is recommended that the inside of the parapet be properly prepared to receive the new base flashing. In many instances, it is prudent to re-skin the parapet with sheathing to provide a suitable substrate. Base flashing should not be applied directly to brick parapets because they have irregular surfaces that inhibit good bonding of the base flashing to the brick (see Figure 6-133). Also, if moisture drives into the wall from the exterior side of the parapet with base flashing attached directly to brick, the base flashing can inhibit drying of the wall. Therefore, rather than totally sealing the parapet with membrane base flashing, the upper portion of the brick can be protected by metal panels (as shown in Figure 6-88), which permits drying of the brick.

Figure 6-133: Failed base flashing adhered directly to the brick parapet. Estimated wind speed: 105 mph. Hurricane Katrina (Louisiana, 2005)

When reroofing a steep-sloped roof, if it does not have a continuous ridge vent, but one will be installed as part of the reroofing work, the following are recommended:

- If the decking is intended to act as a diaphragm and the diaphragm loads are high, the typical technique of cutting a slot through the decking (as shown in Figure 6-134) can compromise the integrity of the diaphragm by interrupting the transfer of diaphragm load from one side of the ridge to the other. For guidance on cutting vent openings that do not compromise diaphragm integrity, see Section 12.7.6 in FEMA 55. Note: An updated version of FEMA 55 is expected to be released in 2011.
- To prevent weakening of joists or trusses (as occurred at Figure 6-134), prior to slotting the deck, the depth of the saw should be adjusted so that the blade is only slightly below the bottom of the deck.

Figure 6-134: During a reroofing project a slot was cut in the plywood deck in order to allow air to flow from the attic to a new continuous ridge vent. The cutting depth of the saw was not adjusted for the thickness of the deck. The top 1½ inch of each truss and a portion of the metal nailing plate was inadvertently cut.

6.4.3 Exterior-Mounted Equipment

Exterior-mounted equipment on existing schools should be carefully examined and evaluated.

6.4.3.1 HVAC Units, Condensers, Fans, Exhaust Stacks, and Ductwork

Where HVAC units are inadequately anchored to their curbs, or where the curb is inadequately attached, cables with turnbuckles should be attached to pipe anchors attached to the deck (see Figure 6-135). The pipe anchors should be stiff so that the top of the anchor is not pulled towards the unit by the cable (otherwise, the unit may lift and shift off the curb).

Figure 6-135: To strengthen attachment of this HVAC unit, robust pipe anchors were attached to the deck and cables with turnbuckles installed.

If HVAC units have inadequately attached sheet metal hoods (see Figure 6-136), sheet metal straps can be economically installed between the top of the hood and the side of the unit. Equipment access panels may also need to be modified to resist wind loads as discussed in Section 6.3.4.1. Besides avoiding damage to the unit, these types of retrofits can prevent blown-off hoods and panels from causing injury and damaging the roof membrane or other building components.

Figure 6-136: At this school, the hood on this HVAC unit was inadequately attached. A strap between the hood and unit can be economically installed to avoid this problem. Estimated wind speed: 110 mph. Hurricane Ike (Texas, 2008)

Where condensers are mounted to curbs that are adequately anchored to the deck, straps can be installed as shown in Figure 6-95 if the condenser attachment is inadequate. If condensers are mounted on sleepers (see Figure 6-137), then the condensers should be re-mounted and anchored to curbs or stands that are anchored to the roof deck.

If exhaust stacks such as those shown in Figure 6-137 are inadequately anchored, guys attached to pipe anchors such as those shown in Figure 6-135 should be installed. To avoid blow-off of rain caps as shown in Figure 6-137, additional straps or screws may need to be installed.

Figure 6-137: These condensers were simply mounted on wood sleepers that rested on the roof surface. Note the damaged exhaust stacks and missing rain caps (red oval). Estimated wind speed: 105 mph. Hurricane Katina (Mississippi, 2005)

To avoid blow-off of fan cowlings, installation of cables is recommended as discussed in Section 6.3.4.1.

If rooftop ductwork exists, its wind resistance should be carefully evaluated. As shown in Figure 6-138, blown-off ducts can allow a substantial amount of rain to enter a building.

Fastening rooftop equipment to curbs, as discussed in Section 6.3.4.1, is a cost-effective approach to minimize wind-induced problems.

Figure 6-138:
Two large openings (red rectangle and inset) through the roof were left after the ductwork blew away. Estimated wind speed: 130 mph. Hurricane Katrina (Mississippi, 2005)

6.4.3.2 Antenna (Communications Mast)

Antenna collapse is very common. Besides loss of communications, collapsed masts can puncture roof membranes or cause other building damage as shown in Figure 6-139. This case also demonstrates the benefits of a high parapet. Although the roof still experienced high winds that blew off this penthouse door, the parapet prevented the door from blowing off the roof (red arrow in Figure 6-139).

6.4.3.3 Lightning Protection Systems

Adhesively attached conductor connectors and pronged splice connectors typically have not provided reliable attachment during hurricanes. To provide more reliable attachment for LPSs located in hurricane-prone regions where the basic wind speed is 135 mph[39] or greater, it is recommended that attachment modifications based on the guidance given in Section 6.3.4.4 be used.

39 The 135-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 100 mph.

Figure 6-139: The antenna collapsed and was whipped back and forth across the roof membrane. Hurricane Andrew (Florida, 1992)

6.5 Occupant Protection Best Practices in Tornado- and Hurricane-Prone Regions

Strong and violent tornadoes may reach wind speeds substantially greater than those recorded in the strongest hurricanes. The wind pressures that these tornadoes can exert on a building are tremendous, and far exceed the minimum pressures derived from building codes. The same can be said, but to a lesser extent for Category 4 and 5 hurricanes that may make landfall with wind speeds that exceed the basic (design) wind speed by 50 mph or more.

Strong and violent tornadoes can generate very powerful missiles. Experience shows that large and heavy objects, including vehicles (see Figure 6-140), can be hurled into buildings at high speeds. The missile sticking out of the school roof in the foreground of Figure 6-141 is a double 2-inch by 6-inch wood member. The portion sticking out of the roof is 13 feet long. It penetrated a ballasted ethylene propylene diene monomer (EPDM) membrane, approximately 3 inches of polyisocyanurate roof insulation, and the steel roof deck. The missile lying on the roof just beyond is a 2-inch by 10-inch by 16-foot long wood member.

Terrorist threat: If it is desired to incorporate a tornado safe room, and if it is also desired for the safe room to provide protection from terrorism, refer to FEMA 428 and 453 for additional shelter enhancements.

Figure 6-140: Greensburg Tornado (Kansas, 2007)

Figure 6-141: A violent tornado showered the roof with missiles (Oklahoma, 1999)

For schools located in tornado-prone regions (as defined in the text box on the following page) and for schools that will be used for hurricane shelters, it is recommended that a safe room be incorporated within the school to provide occupant protection. For safe room design, see FEMA 361.

Note: The 2009 edition of the IBC references ICC 500 for the design and construction of hurricane and tornado shelters. However, while ICC 500 specifies shelter criteria, it does not require shelters. ICC 500 is available to those who voluntarily desire to use it and to jurisdictions for adoption. FEMA 361 references much of the ICC 500 Standard.

In this manual, the term "**tornado-prone regions**" refers to those areas of the United States where the number of recorded EF3, EF4, and EF5 tornadoes per 2,470 square miles is 5 or greater per year (see Figure 6-141). However, a school district may decide to use other frequency values (e.g., 1 or greater, 11 or greater, or greater than 15) in defining whether a school is in a tornado-prone area. In this manual, a tornado safe room is recommended for all schools in tornado-prone regions.

Where the frequency value is 1 or greater, and the school does not have a tornado safe room or shelter, the best available refuge areas should be identified, as discussed at the end of this Section.

Existing Schools without Tornado Shelters

Where the number of recorded EF3, EF4, and EF5 tornadoes per 2,470 square miles is one or greater (see Figure 6-142), the best available refuge areas should be identified if the school does not have a tornado safe room. FEMA 431 provides useful information for building owners, architects, and engineers who perform evaluations of existing facilities.

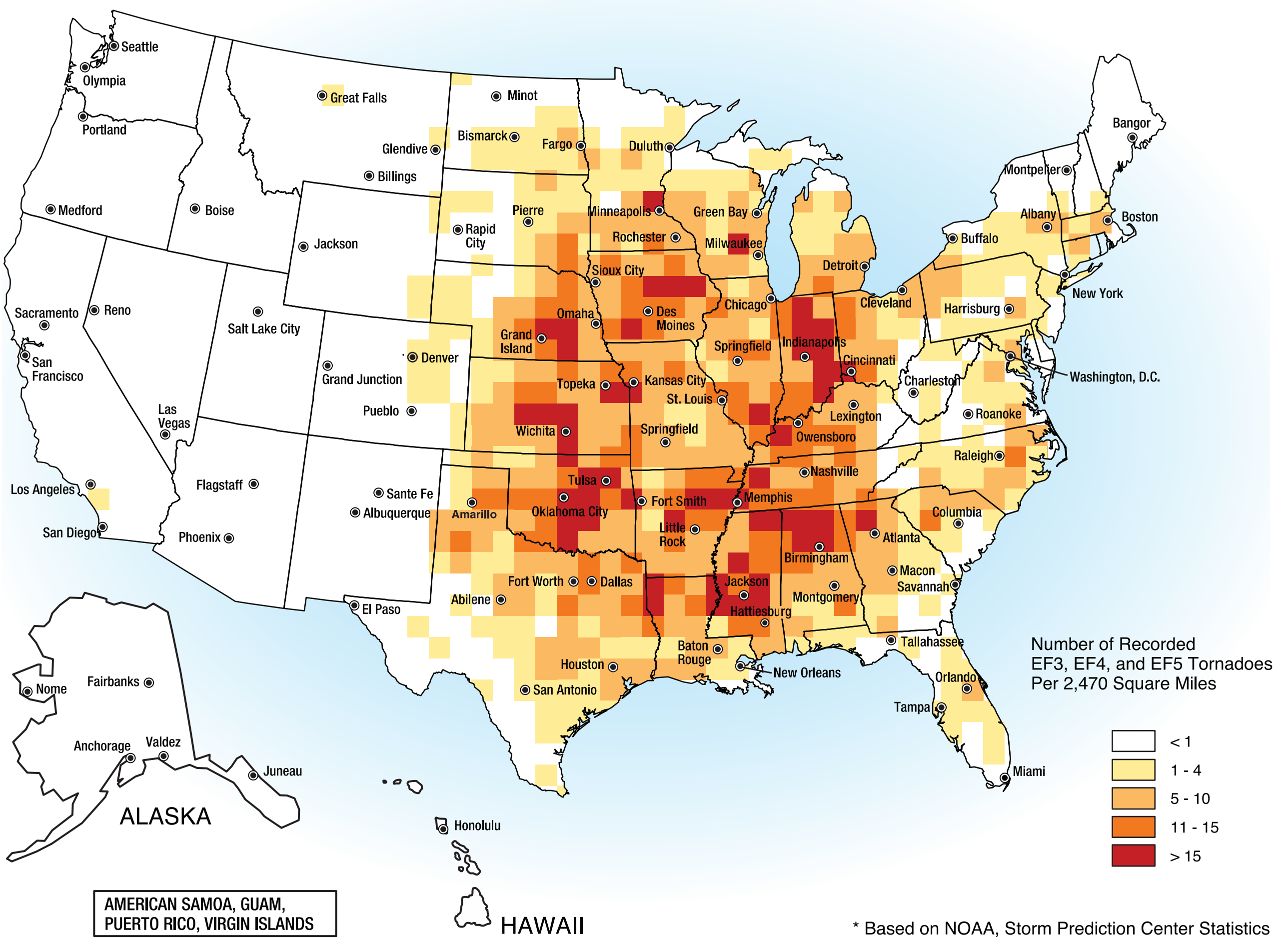


Figure 6-142: Frequency of recorded EF3, EF4, and EF5 tornadoes (1950–2006)

"**Safe room**" and "**shelter**" are two terms that have been used interchangeably in past publications, guidance documents, and other shelter-related materials. However, with the release of the ICC 500 standard, there is a need to identify or describe shelters that meet the FEMA criteria that provide near-absolute life-safety protection and those that meet the ICC 500 standard (which is simply life-safety protection). To help clarify the difference between shelters designed to the ICC 500 standard and the FEMA 361 guidance, FEMA 361 refers to all shelters constructed to meet the FEMA criteria as safe rooms. These two documents are quite similar and both utilize the same wind speed maps to define the tornado and hurricane hazards. Further, all safe room criteria in FEMA 361 meet the shelter requirements of the ICC 500. However, a few design and performance criteria in FEMA 361 are more restrictive than some of the requirements found in the ICC 500.

Hurricane safe room and evacuation shelters: In addition to providing criteria for the design and construction of tornado safe rooms, FEMA 361 provides criteria for hurricane safe rooms. Because of differences between wind and wind-borne debris loads induced by tornadoes versus hurricanes, and because of the time difference that the safe room is occupied during these storms, some of the hurricane safe room criteria are different. It is recommended that schools that will be used as hurricane evacuation shelters be designed and constructed in accordance with hurricane safe room guidance given in FEMA 361. In addition, see the recommendations in Section 6.3.5 regarding electrical power, water, and sewer.

Publication 4496 by the American Red Cross (ARC, 2002) provides information regarding assessing existing buildings for use as hurricane evacuation shelters. Unless a school has been specifically designed for use as a shelter, it should only be used as a last resort and only if the school meets the criteria given in ARC 4496.

To minimize casualties in schools, it is very important that the best available refuge areas be identified by a qualified architect or engineer.[40] Once identified, those areas need to be clearly marked so that occupants can reach the refuge areas without delay. Building occupants should not wait for the arrival of a tornado to try to find the best available refuge area in a particular facility; by that time, it will be too late. If refuge areas have not been identified beforehand, occupants will take cover wherever they can, frequently in very dangerous places. Corridors and other refuge areas sometimes provide protection, but they can also be death traps. The school shown in Figure 6-143 did not have a safe room. However, it did have a best available refuge area, which was occupied during a tornado. Unfortunately, collapsing occurred and eight students died.

Retrofitting a shelter space inside an existing school can be very expensive. An economical alternative is an addition that can function as a safe room as well as serve another purpose. This approach works well for many schools. For very large schools, constructing two or more safe room additions should be considered in order to reduce the time it takes to reach the safe room (often there is ample warning time, but sometimes an approaching tornado is not noticed until a few minutes before it strikes).

40 The occupants of a "best available refuge area" are still vulnerable to death and injury if the refuge area was not specifically designed as a tornado safe room.

Figure 6-143 : Unreinforced masonry walls and hollow-core concrete roof planks collapsed. Enterprise Tornado (Alabama, 2007)

Portable Classrooms: Portable classrooms should not be occupied during times when a tornado watch has been issued by the National Weather Service (a watch means that conditions are favorable for tornado development). Do not wait for issuance of a tornado warning (i.e., a tornado has been spotted) by the National Weather Service to seek refuge in the main school building. If a tornado is nearby, students could be caught outdoors.

6.6 Checklist For Building Vulnerability of Schools Exposed to High Winds

The Building Vulnerability Assessment Checklist (Table 6-2) is a tool that can help in assessing the vulnerability of various building components during the preliminary design of a new building, or the rehabilitation of an existing building. In addition to examining design issues that affect vulnerability to high winds, the checklist also examines the potential adverse effects on the functionality of the critical and emergency systems upon which most schools depend. The checklist is organized into separate sections, so that each section can be assigned to a subject expert for greater accuracy of the examination. The results should be integrated into a master vulnerability assessment to guide the design process and the choice of appropriate mitigation measures.

Table 6-2: Checklist for building vulnerability of schools exposed to high winds

Vulnerability Sections	Guidance	Observations
General		
What is the age of the facility, and what building code and edition was used for the design of the building?	Substantial wind load improvements were made to the model building codes in the 1980s. Many buildings constructed prior to these improvements have structural vulnerabilities. Since the 1990s, several additional changes have been made, the majority of which pertain to the building envelope. Older buildings, not designed and constructed in accordance with the practices developed since the early 1990s, are generally more susceptible to damage than newer buildings.	
Is the school older than 5 years, or is it located in a zone with basic wind speed greater than 120 mph?†	In either case, perform a vulnerability assessment with life-safety issues as the first priority, and property damage and interruption of service as the second priority.	
Site		
What is the design wind speed at the site? Are there topographic features that will result in wind speed-up?	ASCE 7	
What is the wind exposure on site?	Avoid selecting sites in Exposure D, and avoid escarpments and hills.	
Are there trees or towers on site?	Avoid trees and towers near the facility. If the site is in a hurricane-prone region, avoid trees and towers near primary access roads.	
Road access	Provide two separate means of access.	
Is the site in a hurricane-prone region?	ASCE 7. If yes, follow hurricane-resistant design guidance.	
If in a hurricane-prone region, are there aggregate-surfaced roofs within 1,500 feet of the facility?	Remove aggregate from existing roofs. If the buildings with aggregate are owned by other parties, attempt to negotiate the removal of the aggregate.	
Architectural		
Will the facility be used as a shelter?	If yes, refer to FEMA 361.	
Are there interior non-load-bearing masonry walls?	Design for wind load. See Section 6.3.3.4.	
Are there multiple buildings on site in a hurricane-prone region?	Provide enclosed walkways between buildings that will be occupied during a hurricane.	
Structural Systems	Section 6.3.2	
Is a pre-engineered building being considered?	If yes, ensure the structure is not vulnerable to progressive collapse. If a pre-engineered building exists, evaluate to determine if it is vulnerable to progressive collapse.	

† The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

Table 6-2: Checklist for building vulnerability of schools exposed to high winds

Vulnerability Sections	Guidance	Observations
Structural Systems (cont.)	Section 6.3.2	
Is precast concrete being considered?	If yes, design the connections to resist wind loads. If precast concrete elements exist, verify that the connections are adequate to resist the wind loads.	
Are exterior load-bearing walls being considered?	If yes, design as MWFRS and C&C.	
Is an FM Global-rated roof assembly specified?	If yes, comply with FM Global deck criteria.	
Is there a covered walkway or canopy?	If yes, use “free roof” pressure coefficients from ASCE 7. Canopy decks and canopy framing members on older buildings often have inadequate wind resistance. Wind-borne debris from canopies can damage adjacent buildings and cause injury.	
Is the site in a hurricane-prone region?	A reinforced cast-in-place concrete structural system, and reinforced concrete or fully grouted and reinforced CMU walls, is recommended.	
Is the site in a tornado-prone region?	If yes, provide occupant protection. See FEMA 361. For existing schools that do not have safe rooms, see FEMA 431.	
Do portions of the existing facility have long-span roof structures (e.g., a gymnasium)?	Evaluate structural strength, since older long-span structures often have limited uplift resistance.	
Is there adequate uplift resistance of the existing roof deck and deck support structure?	The 1979 (and earlier) SBC and UBC, and 1984 (and earlier) BOCA/NBC, did not prescribe increased wind loads at roof perimeters and corners. Decks (except cast-in-place concrete) and deck support structures designed in accordance with these older codes are quite vulnerable. The strengthening of the deck attachment and deck support structure is recommended for older buildings.	
Are there existing roof overhangs that cantilever more than 2 feet?	Overhangs on older buildings often have inadequate uplift resistance.	
Building Envelope	Section 6.3.3	
Exterior doors, walls, roof systems, windows, and skylights.	Select materials and systems, and detail, to resist wind and wind-driven rain.	
Are soffits considered for the building?	Design to resist wind and wind-driven water infiltration. If there are existing soffits, evaluate their wind and wind-driven rain resistance. If the soffit is the only element preventing wind-driven rain from being blown into an attic space, consider strengthening the soffit.	
Are there elevator penthouses on the roof?	Design to prevent water infiltration at walls, roof, and mechanical penetrations.	
Is a low-slope roof considered on a site in a hurricane-prone region?	A minimum 3-foot parapet is recommended on low-slope roofs.	

Table 6-2: Checklist for building vulnerability of schools exposed to high winds

Vulnerability Sections	Guidance	Observations
Building Envelope (cont.)	Section 6.3.3	
Are there existing sectional or rolling doors?	Older doors often lack sufficient wind resistance.	
Does the existing building have large windows or curtain walls?	If an older building, evaluate their wind resistance.	
Does the existing building have exterior glazing (windows, glazed doors, or skylights)?	If the building is in a hurricane-prone region, replace with impact-resistant glazing, or protect with shutters.	
Does the existing building have operable windows?	If an older building, evaluate its wind-driven rain resistance via ASTM E 1105.	
Are there existing exterior non-load-bearing masonry walls?	If the building is in a hurricane- or tornado-prone region, strengthen or replace.	
Are there existing brick veneer, EIFS, or stucco exterior coverings?	If the building is in a hurricane-prone region, evaluate attachments. To evaluate wind resistance of EIFS, see ASTM E 2359.	
Are existing exterior walls resistant to wind-borne debris?	If the building will be used as a hurricane evacuation shelter, but was not designed and constructed in accordance with FEMA 361, consider enhancing debris resistance.	
Does the existing roof have a fully adhered membrane?	To evaluate uplift resistance, see ASTM E 907.	
Are there existing ballasted single-ply roof membranes?	Determine if they are in compliance with ANSI/SPRI RP-4. If non-compliant, take corrective action.	
Does the existing roof have aggregate surfacing, lightweight pavers, or cementitious-coated insulation boards?	If the building is in a hurricane-prone region, replace the roof covering to avoid blow-off.	
Does the existing roof have edge flashing, coping, or gutters?	Evaluate the adequacy of the attachment.	
Does the existing roof system incorporate a secondary membrane?	If not, and if the building is in a hurricane-prone region, reroof and incorporate a secondary membrane into the new system.	
Does the existing building have a brittle roof covering, such as slate or tile?	If the building is in a hurricane-prone region, consider replacing with a non-brittle covering, particularly if the building will be used as a hurricane evacuation shelter.	
Exterior-Mounted Mechanical Equipment	Section 6.3.4.1	
Is there mechanical equipment mounted outside at grade or on the roof?	Anchor the equipment to resist wind loads. If there is existing equipment, evaluate the adequacy of the attachment, including attachment of cowlings, access panels, ducts, and gas lines.	
Are there penetrations through the roof?	Design intakes and exhausts to avoid water leakage.	
Is the site in a hurricane-prone region?	If yes, place the equipment in a penthouse, rather than exposed on the roof.	

Table 6-2: Checklist for building vulnerability of schools exposed to high winds

Vulnerability Sections	Guidance	Observations
Exterior-Mounted Electrical and Communications Equipment	Section 6.3.4.3	
Are there antennae (communication masts) or satellite dishes?	If there are existing antennae or satellite dishes and the building is located in a hurricane-prone region, evaluate wind resistance. For antennae evaluation, see Chapter 15 of ANSI/TIA-222-G.	
Does the building have an LPS?	See Sections 6.3.4.3 and 6.3.4.4 for LPS attachment. For existing LPSs, evaluate wind resistance (Section 6.4.3.3)	
Municipal Utilities		
Will the facility be used as a hurricane evacuation shelter?	See Section 6.3.5 for emergency power, water, and sewer recommendations.	
Is the emergency generator housed in a wind- and debris-resistant enclosure?	If not, build an enclosure to provide debris protection.	
Is the emergency generator's wall louver protected from wind-borne debris?	If not, install a louver or screen wall to provide debris impact protection.	

6.7 References and Sources of Additional Information

Note: FEMA publications may be obtained at no cost by calling (800) 480-2520, or by downloading from the library/publications section online at http://www.fema.gov.

American Association of State Highway and Transportation Officials (AASHTO), 2009. *Standard Specifications for Structural Supports for Highway Signs, Luminaires and Traffic Signal*s, LTS-4-5.

American Institute of Architects (AIA), 1997. *Buildings at Risk: Wind Design Basics for Practicing Architects.*

American National Standards Institute (ANSI), 2003. *Wind Design Standard for Edge Systems Used in Low Slope Roofing Systems*, ANSI/SPRI ES-1.

ANSI, 2008. *Wind Design Standard for Ballasted Single-Ply Roofing Systems*, ANSI/SPRI RP-4.

ANSI/Telecommunications Industry Association (TIA), 2009. *Structural Standard for Antenna Supporting Structures and Antennas,* ANSI/TIA-222-G, Addendum 2, December 2009.

American Red Cross (ARC), 2002. *Standards for Hurricane Evacuation Shelter Selection*, Publication 4496, July 1992, rev. January 2002.

American Society of Civil Engineers (ASCE), 2005. *Minimum Design Loads for Buildings and Other Structures,* ASCE 7-05, Structural Engineering Institute, Reston, VA.

ASCE, 2010. *Minimum Design Loads for Buildings and Other Structures,* 2010 Edition, ASCE 7-10, Structural Engineering Institute, Reston, VA.

American Society for Testing and Materials (ASTM), 2004. *Standard Test Method for Field Testing Uplift Resistance of Adhered Membrane Roofing Systems,* ASTM E 907-96.

ASTM, 2005a. *Standard Test Method for Performance of Exterior Windows, Curtain Walls, Doors, and Impact Protective Systems Impacted by Missile(s) and Exposed to Cyclic Pressure Differentials,* ASTM E 1886.

ASTM, 2005b. *Standard Test Method for Structural Performance of Sheet Metal Roof and Siding Systems by Uniform Static Air Pressure Difference,* ASTM E 1592.

ASTM, 2006a. *Standard Test Method for Structural Performance of Exterior Windows, Curtain Walls, and Doors by Cyclic Static Air Pressure Differential,* ASTM E 1233.

ASTM, 2006b. *Test Method for Field Pull Testing of an In-Place Exterior Insulation and Finish System Clad Wall Assembly,* ASTM E 2359.

ASTM, 2007. *Standard Practice for Installation of Exterior Windows, Doors and Skylights,* ASTM E 2112.

ASTM, 2008. *Standard Test Method for Field Determination of Water Penetration of Installed Exterior Windows, Skylights, Doors, and Curtain Walls by Uniform or Cyclic Static Air Pressure Difference,* ASTM E 1105-00.

ASTM, 2009a. *Standard Specification for Performance of Exterior Windows, Curtain Walls, Doors and Impact Protective Systems Impacted by Windborne Debris in Hurricanes,* ASTM E 1996.

American Society of Heating, Refrigerating and Air Conditioning Engineers (ASHRAE), 2006. *Calculating Wind Loads and Anchorage Requirements for Rooftop Equipment.*

ASHRAE, 2007a. *Standard 62.1 User's Manual.*

ASHRAE, 2007b. *Ventilation for Acceptable Indoor Air Quality, Standard 62.1.*

Baskaran, B, and T.L. Smith, 2005. *A Guide for the Wind Design of Mechanically Attached Flexible Membrane Roofs,* Institute for Research in Construction, National Research Council of Canada.

Door and Access Systems Manufacturers Association, 2008. *Connecting Garage Door Jambs to Building Framing,* Technical Data Sheet #161, December 2003, revised May 2008.

Edwards, Roger, 2009. The Online Tornado FAQ, Storm Prediction Center, NOAA. www.spc.noaa.gov/faq/tornado/#History, last modified December 31, 2009.

Factory Mutual Research, *Approval Guide,* Norwood, MA, updated quarterly.

Federal Emergency Management Agency (FEMA), 1992. B*uilding Performance: Hurricane Andrew in Florida*, FEMA FIA-22, Washington, DC, December 1992.

FEMA, 1993. *Building Performance: Hurricane Iniki in Hawaii,* FEMA FIA-23, Washington, DC, January 1993.

FEMA, 1996. *Corrosion Protection for Metal Connectors in Coastal Areas,* FEMA Technical Bulletin 8-96, Washington, DC, August 1996.

FEMA, 1998. *Typhoon Paka: Observations and Recommendations on Building Performance and Electrical Power Distribution System,* FEMA-1193-DR-GU, Washington, DC, March 1998.

FEMA, 1999a. *Hurricane Georges in Puerto Rico*, FEMA 339, Washington, DC, March 1999.

FEMA, 1999b. *Oklahoma and Kansas Midwest Tornadoes of May 3, 1999*, FEMA 342, Washington, DC, October 1999.

FEMA, 2000. *Coastal Construction Manual*, FEMA 55, CD (3rd Edition).

FEMA, 2002. *Installing Seismic Restraints for Mechanical Equipment*, FEMA 412, Washington, DC, December 2002.

FEMA, 2003a. *Primer to Design Safe School Projects in Case of Terrorist Attacks*, FEMA 428, December 2003.

FEMA, 2003b. *Tornado Protection, Selecting Safe Areas in Buildings*, FEMA 431, Washington, DC, October 2003.

FEMA, 2004a. *Installing Seismic Restraints for Duct and Pipe*, FEMA 414, Washington, DC, January 2004.

FEMA, 2004b. *Installing Seismic Restraints for Electrical Equipment*, FEMA 413, Washington, DC, January 2004.

FEMA, 2005a. *MAT Report: Hurricane Charley in Florida*, FEMA 488, Washington, DC, April 2005.

FEMA, 2005b. *MAT Report: Hurricane Ivan in Alabama and Florida,* FEMA 489, Washington, DC, August 2005.

FEMA, 2006a. *Design Guidance for Shelters and Safe Rooms,* FEMA 453, Washington, DC.

FEMA, 2006b. *MAT Report: Hurricane Katrina in the Gulf Coast,* FEMA 549, Washington, DC, July 2006.

FEMA, 2007. *Design Guide for Improving Critical Facility Safety from Flooding and High Winds*, FEMA 543, Washington, DC, January 2007.

FEMA, 2008a. *Design and Construction Guidance for Community Safe Rooms*, FEMA 361, Washington, DC, November 2008.

FEMA, 2008b. *Taking Shelter From the Storm: Building a Safe Room Inside Your House*, FEMA 320, Washington, DC, August 2008.

FEMA, 2009. *MAT Report: Hurricane Ike in Texas and Louisiana*, FEMA P-757, Washington, DC, April 2009.

FEMA, 2010. *Home Builder's Guide to Coastal Construction Technical Fact Sheet Series*, FEMA P-499, December 2010.

FM Global, dates vary. *Loss Prevention Data for Roofing Contractors*, Norwood, MA.

Institute of Electrical and Electronics Engineers, Inc. (IEEE), 2008. *National Electrical Code,* NFPA 70.

International Code Council (ICC), 2008. *ICC/NSSA Standard on the Design and Construction of Storm Shelters*, ICC 500-2008, Country Club Hills, IL.

ICC, 2009. 2006 *International Building Code*, ICC IBC-2009, February 2009.

National Research Council of Canada, 2005. *Wind Design Guide for Mechanically Attached Flexible Membrane Roofs*, B1049.

6.8 Glossary of High Wind Protection Terms

Astragal. The center member of a double door, which is attached to the fixed or inactive door panel.

Basic wind speed. A 3-second gust speed at 33 feet above the ground in Exposure C. (Exposure C is flat open terrain with scattered obstructions having heights generally less than 30 feet.) Note: Since 1995, ASCE 7 has used a 3-second peak gust measuring time. A 3-second peak gust is the maximum instantaneous speed with a duration of approximately 3 seconds. A 3-second peak gust speed could be associated with a given windstorm (e.g., a particular storm could have a 40-mph peak gust speed), or a 3-second peak gust speed could be associated with a design level event (e.g., the basic wind speed prescribed in ASCE 7).

Building, enclosed. A building that does not comply with the requirements for open or partially enclosed buildings.

Building, open. A building having each wall at least 80 percent open. This condition is expressed by an equation in ASCE 7.

Building, partially enclosed. A building that complies with both of the following conditions:

1. The total area of openings in a wall that receives positive external pressure exceeds the sum of the areas of openings in the balance of the building envelope (walls and roof) by more than 10 percent.
2. The total area of openings in a wall that receives positive external pressure exceeds 4 square feet, or 1 percent of the area of that wall, whichever is smaller, and the percentage of openings in the balance of the building envelope does not exceed 20 percent.

These conditions are expressed by equations in ASCE 7.

Building, simple diaphragm. An enclosed or partially enclosed building in which wind loads are transmitted through floor and roof diaphragms to the vertical main wind-force resisting system.

Components and cladding (C&C). Elements of the building envelope that do not qualify as part of the main wind-force resisting system.

Coping. The cover piece on top of a wall exposed to the weather, usually made of metal, masonry, or stone, and sloped to carry off water.

Downburst. Also known as a microburst. A powerful downdraft associated with a thunderstorm.

Down-slope wind. A wind blowing down the slope of mountains (frequently occurs in Alaska and Colorado).

Escarpment. Also known as a scarp. With respect to topographic effects, a cliff or steep slope generally separating two levels or gently sloping areas.

Exposure. The characteristics of the ground roughness and surface irregularities in the vicinity of a building. ASCE 7 defines three exposure categories—Exposures B, C, and D.

Extratropical storm. A cyclonic storm that forms outside of the tropical zone. Extratropical storms may be large, often 1,500 miles (2,400 kilometers) in diameter, and usually contain a cold front that extends toward the equator for hundreds of miles.

Flashing. Any piece of material, usually metal or plastic, installed to prevent water from penetrating a structure.

Glazing. Glass or a transparent or translucent plastic sheet used in windows, doors, and skylights.

Glazing, impact-resistant. Glazing that has been shown, by an approved test method, to withstand the impact of wind-borne missiles likely to be generated in wind-borne debris regions during design winds.

Hurricane-prone regions. Areas vulnerable to hurricanes; in the United States and its territories defined as:

1. The U.S. Atlantic Ocean and Gulf of Mexico coasts, where the basic wind speed is greater than 120 miles per hour.[41]
2. Hawaii, Puerto Rico, Guam, U.S. Virgin Islands, and American Samoa.

Impact-resistant covering. A covering designed to protect glazing, which has been shown by an approved test method to withstand the impact of wind-borne missiles likely to be generated in wind-borne debris regions during design winds.

Importance factor, I. A factor that accounts for the degree of hazard to human life and damage to property. Importance factors are given in

41 The 120-mph basic wind speed is based on ASCE 7-10, Risk Category III and IV buildings. If ASCE 7-05 or an earlier version is used, the equivalent wind speed trigger is 90 mph.

ASCE 7. Note: In ASCE 7-10, the importance factor was eliminated for wind loads because the degree of hazard to human life and property damage is accounted for by the proper map selection.

Main wind-force resisting system. An assemblage of structural elements assigned to provide sup-port and stability for the overall structure. The system generally receives wind loading from more than one surface.

Mean roof height, h. The average of the roof eave height and the height to the highest point on the roof surface, except that, for roof angles of less than or equal to 10 degrees, the mean roof height shall be the roof eave height.

Missiles. Debris that could become propelled into the wind stream.

Nor'easter. Nor'easters are non-tropical storms that typically occur in the eastern United States, any time between October and April, when moisture and cold air are plentiful. They are known for dumping heavy amounts of rain and snow, producing hurricane-force winds, and creating high surfs that cause severe beach erosion and coastal flooding. A nor'easter is named for the winds that blow in from the northeast and drive the storm along the east coast and the Gulf Stream, a band of warm water that lies off the Atlantic Coast.

Openings. Apertures or holes in the building envelope that allow air to flow through the building envelope. A door that is intended to be in the closed position during a windstorm would not be considered an opening. Glazed openings are also not typically considered openings. However, if the building is located in a wind-borne debris region and the glazing is not impact-resistant or protected with an impact-resistant covering, the glazing is considered an opening.

Racking. Lateral deflection of a structure resulting from external forces, such as wind or lateral ground movement in an earthquake.

Ridge. With respect to topographic effects, an elongated crest of a hill characterized by strong relief in two directions.

Straight-line wind. A wind blowing in a straight line with wind speeds ranging from very low to very high (the most common wind occurring throughout United States and its territories).

Wind-borne debris regions. Areas within hurricane-prone regions, as defined in ASCE 7.